PB99-126815

NCHRP Report 408

Corrosion of Steel Piling
in Nonmarine Applications

Transportation Research Board
National Research Council

REPORT DOCUMENTATION PAGE	Form Approved OMB No. 0704-0188

Public reporting burden for this collection of information is estimated to average 1 hour response, including the time for reviewing instructions, searching existing data sources, gathering and maintaining the data needed, and completing and reviewing the collection of information. Send comments regarding this burden estimate or any other aspect of this collection of information, including suggestions for reducing this burden, to Washington Headquarters Services, Directorate for Information Operations and Reports, 1215 Jefferson Davis Highway, Suite 1204, Arlington, VA 22202-4302, and to the Office of Management and Budget, Paperwork reduction Project (0704-0188), Washington, DC 20503

1. AGENCY USE ONLY (Leave blank)	2. REPORT DATE 1998	3. REPORT TYPE AND DATES COVERED Final Report	
4. TITLE AND SUBTITLE NCHRP Report 408: Corrosion of Steel Piling in Nonmarine Applications 6. AUTHOR(S): J.A. Beavers and C.L. Durr PB99-126815			5. FUNDING NUMBERS D10-46
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) CC Technologies Laboratories, Inc. Dublin, OH			8. PERFORMING ORGANIZATION REPORT NUMBER HR 10-46
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES) American Association of State Highway and Transportation Officials 444 North Capitol Street, N.W. Suite 249 Washington, D.C. 20001			10. SPONSORING/MONITORING AGENCY REPORT NUMBER
11. SUPPLEMENTARY NOTES Sponsored in cooperation with the Federal Highway Administration			
12a. DISTRIBUTION/AVAILABILITY STATEMENT Available 2101 Constitution Avenue, N.W., Washington, D.C. 20418		from: Transportation Research Board	12b. DISTRIBUTION CODE: unlimited

13. ABSTRACT (Maximum 200 words)
The report contains the findings of a study to provide knowledge on the magnitude of the problem of steel piling corrosion and to synthesize the current state of practice in evaluating and predicting corrosion. A recommended practice for the assessment of steel piling in nonmarine applications and a strategic plan to develop means to determine the condition and to estimate the useful life of steel piling are provided. The contents of this report will be of immediate interest to geotechnical engineers and bridge engineers.

14. SUBJECT TERMS Bridges, Other Structures, and Hydraulics and Hydrology; Soils, Geology, and Foundations	15. NUMBER OF PAGES
	16. PRICE CODE

17. SECURITY CLASSIFICATION Unclassified	18. SECURITY CLASSIFICATION OF THIS PAGE Unclassified	19. SECURITY CLASSIFICATION OF ABSTRACT Unclassified	20. LIMITATION OF ABSTRACT

Report 408

Corrosion of Steel Piling in Nonmarine Applications

J. A. BEAVERS and C. L. DURR
CC Technologies Laboratories, Inc.
Dublin, Ohio

Subject Areas

Bridges, Other Structures, and Hydraulics and Hydrology
Soils, Geology, and Foundations

TRANSPORTATION RESEARCH BOARD
NATIONAL RESEARCH COUNCIL

NATIONAL ACADEMY PRESS
Washington, D.C. 1998

NATIONAL COOPERATIVE HIGHWAY RESEARCH PROGRAM

Systematic, well-designed research provides the most effective approach to the solution of many problems facing highway administrators and engineers. Often, highway problems are of local interest and can best be studied by highway departments individually or in cooperation with their state universities and others. However, the accelerating growth of highway transportation develops increasingly complex problems of wide interest to highway authorities. These problems are best studied through a coordinated program of cooperative research.

In recognition of these needs, the highway administrators of the American Association of State Highway and Transportation Officials initiated in 1962 an objective national highway research program employing modern scientific techniques. This program is supported on a continuing basis by funds from participating member states of the Association and it receives the full cooperation and support of the Federal Highway Administration, United States Department of Transportation.

The Transportation Research Board of the National Research Council was requested by the Association to administer the research program because of the Board's recognized objectivity and understanding of modern research practices. The Board is uniquely suited for this purpose as it maintains an extensive committee structure from which authorities on any highway transportation subject may be drawn; it possesses avenues of communications and cooperation with federal, state and local governmental agencies, universities, and industry; its relationship to the National Research Council is an insurance of objectivity; it maintains a full-time research correlation staff of specialists in highway transportation matters to bring the findings of research directly to those who are in a position to use them.

The program is developed on the basis of research needs identified by chief administrators of the highway and transportation departments and by committees of AASHTO. Each year, specific areas of research needs to be included in the program are proposed to the National Research Council and the Board by the American Association of State Highway and Transportation Officials. Research projects to fulfill these needs are defined by the Board, and qualified research agencies are selected from those that have submitted proposals. Administration and surveillance of research contracts are the responsibilities of the National Research Council and the Transportation Research Board.

The needs for highway research are many, and the National Cooperative Highway Research Program can make significant contributions to the solution of highway transportation problems of mutual concern to many responsible groups. The program, however, is intended to complement rather than to substitute for or duplicate other highway research programs.

NOTICE

FOREWORD

By Staff
Transportation Research
Board

This report contains the findings of a study to provide knowledge on the magnitude of the problem of steel piling corrosion and to synthesize the current state of practice in evaluating and predicting corrosion. A recommended practice for the assessment of steel piling in nonmarine applications and a strategic plan to develop means to determine the condition and to estimate the useful life of steel piling are provided. The contents of this report will be of immediate interest to geotechnical engineers and bridge engineers.

Historically, steel piling has been used to support structures without concern for loss of section from corrosion. In many cases, existing steel-pile foundations are used to support rehabilitated structures without an assessment of the piling condition. Steel piles exposed during some recent bridge-pier construction operations have revealed severe corrosion damage. Bridge engineers and owners want guidance on the condition evaluation of existing steel piling, on the estimated useful life of steel piling, and on steel piling performance models.

Under NCHRP Project 10-46, CC Technologies Laboratories, Inc. prepared an assessment of the magnitude of the problem of corrosion of steel piling in nonmarine applications. A "Recommended Practice" was prepared for assessing the environmental conditions causing corrosion of steel piling, for evaluating the present condition of steel piling, and for estimating the expected service life of new and existing piling. The recommended practice is believed to be of immediate use to bridge engineers and geotechnical engineers.

The contents of this report will help state DOTs identify the corrosion vulnerability of steel piling in their inventories and provide preliminary guidance to address that vulnerability. The strategic research plan identifies a coordinated set of research efforts that should be undertaken to develop means to determine the condition and to estimate the useful life of steel piling.

CONTENTS

CORROSION OF STEEL PILING IN NONMARINE APPLICATIONS

SUMMARY   Historically, steel piling has been used to support structures with little concern given to loss of section from corrosion. Recently, examinations of steel piles exposed during bridge-pier construction operations have revealed severe corrosion damage. The long-range objective of research in this area is to develop means to determine the condition and to estimate the useful life of steel piling. This information will assist bridge engineers and owners in their decisionmaking with regard to the use of existing and new steel-pile supports for structures.

The specific objectives of NCHRP Project 10-46 were to (1) determine the magnitude of the problem of corrosion of steel piling in soil, (2) assess and synthesize the current state of knowledge for evaluating and predicting the corrosion of steel piling, (3) recommend practices for corrosion evaluation of new and existing steel-pile structures, (4) initiate laboratory testing and model development to predict the useful life of steel piling, and (5) develop a strategic research plan to accomplish the long-range objective. The scope of the project was limited to soil exposure and considered H-, pipe, and sheet piling.

The potential magnitude of the problem of corrosion of steel piling in soil is quite large. Conditions that are conducive to severe corrosion of steel piles are commonly found in pile foundations for bridges. These include the presence of fill soils containing manufactured materials, such as slag, ash, or cinders or soil containing contamination from saltwater runoff or other sources.

Results of the state-of-the-art survey indicate that the controlling mechanism for severe corrosion of steel in soils is thought to be well understood. The presence of moisture and oxygen are required for the corrosion to occur. The specific mechanism is referred to as an oxygen macrocell and is associated with a variation in the concentration of oxygen in the soil from one area to another on the underground structure. These conditions normally occur in stratified soils above the water table. Other factors that have been associated with soil corrosivity include soil resistivity, pH, soil particle size, and the concentration of deleterious anions such as chlorides and sulfates. While the mechanism of underground corrosion and many of the controlling factors are thought to have been identified, prior attempts to predict soil corrosivity have met with limited success. Typically, there is a lot of scatter in the data and the correlation coefficients are low.

2

In NCHRP Project 10-46, a Recommended Practice was prepared using information available from a state-of-the-art survey. The purposes of the practice were to (1) summarize the current knowledge on corrosion of piling in soils, (2) describe procedures to assess soil corrosivity and the present condition of existing steel piling, and (3) offer guidance in corrosion mitigation and the use of steel piling in new or rehabilitated structures.

Laboratory and field testing were conducted to evaluate the Recommended Practice, address unresolved issues identified in the state-of-the-art survey, and establish a framework for a model for predicting the corrosion of steel piling in soil environments. Results of this preliminary testing indicate that uniform corrosion in the corrosive soil strata may be a major contributor to pile failure. This finding was unanticipated, but the tests may have been too short for macrocells to develop properly. Macrocells may dominate corrosion behavior in longer tests and on actual pilings.

The results of this preliminary research also indicate that a relatively small number of variables are required to describe the corrosivity of a field site. These variables include soil resistivity, pH, soil particle size, and the position of the pile with respect to the water table. A simple decision tree on the basis of this information was incorporated into the Recommended Practice. When the procedures outlined in the Recommended Practice were tested out on case histories found in the literature, it was found that the decision tree could correctly identify the potential corrosivity of a field site in more than 80 percent of the cases.

The Strategic Research Plan was prepared to meet the long-range objective of developing the means to determine the condition and to estimate the useful life of steel piling. The plan emphasizes field corrosion rate measurements and the development of a corrosion prediction model. Unresolved issues from the ongoing work and issues outside the original scope of this work are addressed in the research plan.

CHAPTER 1

INTRODUCTION AND RESEARCH APPROACH

Historically, steel piling has been used to support structures with little concern given to loss of section from corrosion. Existing steel pile foundations are also being used to support rehabilitated structures without assessing the condition of the steel piling. Recently, examinations of steel piles exposed during bridge-pier construction operations have revealed severe corrosion damage. Extensive corrosion damage has also been observed in related structures, such as reinforced soil structures.

Corrosion of structural steel in soils is electrochemical in nature and is caused by the presence of oxygen and moisture in the soil. Corrosion is most likely to occur at or above the water table in disturbed stratified soils having low resistivity. For example, fill soils containing manufactured materials such as cinders, slag, or ash are known to cause significant corrosion of steel piles. Stray electrical currents flowing in the ground, from sources such as transit systems, can also contribute to corrosion of structural steels in soils.

The long-range objective of research in this area is to develop means to determine the condition and to estimate the useful life of steel piling. This information will assist bridge engineers and owners in their decisionmaking with regard to the use of existing and new steel-pile supports for structures.

The specific objectives of NCHRP Project 10-46 were to (1) determine the magnitude of the problem of corrosion of steel piling in soil, (2) assess and synthesize the current state of knowledge for evaluating and predicting the corrosion of steel piling, (3) recommend practices for corrosion evaluation of new and existing steel-pile structures, (4) initiate laboratory testing and model development to predict the useful life of steel piling, and (5) develop a strategic research plan to accomplish the long-range objective. The scope of the project was limited to soil exposure and considered H-, pipe, and sheet piling.

NCHRP Project 10-46 consisted of eight tasks:

Task 1—Review of Information,
Task 2—Conditions Causing Corrosion,
Task 3—Draft of Recommended Practice,
Task 4—Interim Report,
Task 5—Corrosion Testing and Prediction Model,
Task 6—Strategic Research Plan,
Task 7—Revised Recommended Practice, and
Task 8—Final Report.

The technical approach for each task is given below.

TASK 1—REVIEW OF INFORMATION

The purpose of Task 1 was to review relevant practice, performance data, research findings, and other information related to corrosion and nondestructive evaluation (NDE) of steel piling from both foreign and domestic sources. Corrosion information on related structures was also incorporated into the review. The work in this task was divided into two subtasks: a literature survey and industry interviews.

The literature survey was initiated with a detailed review of government projects relevant to the research including any from FHWA, NCHRP, and state DOTs. The open literature was searched using CORAB®. CORAB® is a CD-ROM version of NACE International's Corrosion Abstracts. The program is run on a PC and contains abstracts of corrosion literature from 1980 to the present. The program contains extensive citations of the open literature from the United States, Europe, and Japan as well as U.S. government literature. Other computerized database sources that have information on the subject matter were searched, including Transportation Research Information Services (TRIS), the Engineering Index, Chemical Abstracts and the National Technical Information Service (NTIS).

Relevant information from state DOTs was obtained by means of a questionnaire, follow-up telephone contacts, and site visits.

TASK 2—CONDITIONS CAUSING CORROSION

The purpose of Task 2 was to document the conditions that cause corrosion of steel piling. The primary input to this task was the information developed in Task 1. The information was analyzed with respect to the possible causes of corrosion of steel piling. The output of Task 2 was a listing of case histories of significant corrosion of steel piling, a summary of the mechanisms of corrosion of steel piling, the identification of environmental factors that affect corrosion of steel piling and a listing of areas of incomplete knowledge.

TASK 3—DRAFT RECOMMENDED PRACTICE

The purpose of Task 3 was to draft a Recommended Practice for (1) assessing the environmental conditions causing

corrosion of steel piling, (2) evaluating the present condition of steel piling, and (3) estimating the expected service life of new and existing piling. The Recommended Practice in this task was written in a format suitable for AASHTO "Recommended Practice" publication. This Recommended Practice will permit future data collection to be performed in a consistent manner and will ensure that the appropriate data are collected that will answer the questions left unanswered by this research.

The Recommended Practice provides guidance and procedures in several areas. These areas include the following:

- Selection of piles for further examination,
- Collection of soil and water samples,
- Analysis of soil and water samples, and
- Examination of removed piles.

TASK 4—INTERIM REPORT

The purpose of Task 4 was to prepare an interim report that documents the findings of Tasks 1 through 3. This report summarized the information developed in Tasks 1 and 2. The Recommended Practice developed in Task 3 was provided as an appendix to the report. The interim report also contained a revised detailed work plan, itemized budget, and projected schedule for Tasks 5 through 8.

TASK 5—CORROSION TESTING AND PREDICTION MODEL

The purposes of Task 5 were (1) to perform laboratory corrosion tests to address unresolved issues identified in Tasks 1 through 3 of the program and (2) to establish a framework for an analytical model for predicting the corrosion of steel piling in soil environments.

Testing was performed in the laboratory on several soils to evaluate three electrochemical techniques for measuring corrosion rates and to assess the relative value of laboratory versus field electrochemical testing. The relative contribution of uniform corrosion and macrocell corrosion on corrosion rates in these soils was also assessed. These three techniques consisted of measurements of corrosion potential, polarization resistance (PR), and galvanic (macrocell) currents.

Laboratory Soil Cells

Three different series of laboratory soil cells were constructed to evaluate the electrochemical techniques discussed above. The first series of cells were used to (1) assess the relative merits of the PR technique proposed for the evaluation of the soil corrosivity at three field sites, described in Task 7, (2) compare corrosion rates calculated from both the PR and weight-loss measurements, and (3)

help determine whether uniform corrosion is a major contributing factor in the corrosion of piling.

In the second series of soil cells, laboratory-sized corrosion probes were embedded in dissimilar soil strata, or soil strata having different moisture contents. The purpose of this series of tests was to (1) measure the magnitude and direction of galvanic current flow between the soil strata, (2) assess the merits of the measurement technique using a prototype lab probe, and (3) compare the corrosion rates calculated from the lab probes with the results from the field corrosion probes that were installed at the three field sites.

The third series of soil cells was constructed for potentiodynamic polarization tests. The purpose of these tests was two-fold. First, the potential and ensuing current data were used in our modeling efforts. Secondly, Tafel slopes were taken directly from the polarization curves and used to calculate corrosion rates from PR measurements.

Field Investigations

Additionally, soil and water analyses were performed on samples obtained from field sites selected in Task 7. The soil parameters analyzed included resistivity, pH, soluble chloride and sulfate concentration, cation exchange capacity (CEC), moisture content, and particle size distribution. Water parameters included pH, conductivity, chloride, sulfate, and bacterial types and counts.

Modeling

Finite Element Analysis (FEA) modeling was used to address two unresolved issues associated with the water table. One issue was the effect of the relative length of the pile above and below the water table on the magnitude of the galvanic effect. The second issue was the maximum distance below the water table where galvanic corrosion is likely to occur.

A statistical modeling approach was used to develop a regression model for predicting the corrosion of steel piling in soil environments. All of the data used in the model development were continuous measures. Since the available data were very limited at this point in time, the regression model development was supplemented with plots of corrosion rates calculated from weight-loss measurements versus each possible independent variable. Additionally, a correlation matrix was created to see if the regression model coefficients were consistent with the correlation coefficients as well as these plots.

TASK 6—STRATEGIC RESEARCH PLAN

The purpose of the Strategic Research Plan was to identify the research necessary to achieve the long-range objective on corrosion of steel piling. The primary focus of the Strategic

Research Plan was on those activities requiring long-term research that are outside the scope of the current research program. The activities in the Strategic Research Plan all feed into a statistical model. The goals of developing this model are to identify soil conditions where unacceptable rates of corrosion of steel piles are likely to occur and to estimate these rates of corrosion. The Strategic Research Plan emphasizes field corrosion rate measurements and the tasks are designed to provide the data required to develop and confirm the model.

TASK 7—REVISED RECOMMENDED PRACTICE

The purpose of Task 7 was to revise the Recommended Practice developed in Task 3. Revisions to the Practice were based on the results of the laboratory tests and predictive modeling performed in Task 5, a field assessment of the Practice performed in Task 7, and input from the project panel. The Recommended Practice was applied to determine its workability and feasibility under actual field conditions. Electrochemical measurements, made with field corrosion probes, were used to supplement the characterization of soil and groundwater corrosivity of the field sites and provide input to the statistical data analysis and modeling efforts.

The Recommended Practice was applied in the field at three sites having varying degrees of corrosivity. These sites, and their anticipated corrosivity, were as follows:

1. Buffalo, New York (Buffalo)—Corrosive,
2. CC Technologies (CCT) in Dublin, Ohio—Non-corrosive, and
3. LaGuardia Airport (LaGuardia) in New York, New York—Non-corrosive.

Soil was sampled at each of the three field sites and groundwater was sampled at two of the sites and analyzed to characterize their corrosivity.

Field Corrosion Probe

Field corrosion probes were designed and constructed for the purpose of performing in situ electrochemical measurements at three field sites. The probe design was modeled after corrosion probes described in the literature.

Corrosion probes were installed at each of the field sites for galvanic current measurements, PR, and corrosion potential. The detailed procedures for performing these measurements are given in this report in Appendixes M, N, and O, respectively.

CHAPTER **2**

FINDINGS

REVIEW OF INFORMATION

A state-of-the-art survey was conducted to review relevant practice, performance data, research findings, and other information related to corrosion and NDE of steel piling from both foreign and domestic sources. Corrosion information on related structures also was incorporated into the review. These structures included

- Metal culverts,
- Mechanically stabilized earth (MSE) structures,
- Building foundations,
- Underground tanks, and
- Underground pipelines.

Appendix A contains a complete list of documents obtained in the literature survey. The documents listed in this appendix primarily pertain to culverts and pilings.

Relevant information from state DOTs also was obtained by means of a questionnaire, follow-up telephone contacts, and site visits. The purposes of the survey were to determine

- Their usage of steel piling,
- Their perception of problems associated with steel-pile corrosion,
- Any prior or current research efforts in this area,
- Present methods, if any, for NDE and corrosion monitoring,
- Their present methods of designing to allow for corrosion (if any),
- Their opinion of what document is appropriate for an AASHTO Recommended Practice, and
- Any planned piling removals.

Table 1 summarizes the indications of corrosion and any techniques used to assess the corrosion as described by respondents who have indicated corrosion of steel piling. Thirty-nine states (78%) responded to the questionnaire. Seventeen (44%) of those responding reported having corrosion problems with piling in soil in nonmarine environments. Of those responding, less than one-half were associated with corrosion in soil. The remainder were associated with corrosion in fresh or brackish (one case) water.

Nine respondents (23%) indicated that they were using or aware of techniques for assessing the dimension, existing condition, or rate of corrosion of steel piling. Three techniques were indicated: (1) physical measurements of exposed pile sections, (2) electrochemical corrosion rate measurements using corrosion probes, and (3) soil analyses in conjunction with a corrosion rate prediction model developed for metal culverts.

A summary of the mechanisms of corrosion of steel piling, the identification of environmental factors that affect corrosion of steel piling, and a listing of case histories of significant corrosion of steel piling are given in Appendix D. A summary of this information, along with areas of incomplete knowledge identified from this information, are given below.

SUMMARY OF CONDITIONS CAUSING CORROSION

It can be concluded from the analysis of the literature and responses to the questionnaires that the overall mechanism responsible for severe corrosion of pilings is thought to be well understood. As described in Appendix D, the presence of moisture and oxygen are required for corrosion to occur. The specific mechanism for the corrosion is referred to as a differential aeration cell (oxygen macrocell) and is associated with a variation in the concentration of oxygen in the soil from one area to another on the underground structure. These conditions normally occur in stratified soils above the water table. Other factors that have been associated with soil corrosivity include soil resistivity, pH, soil particle size, and the concentration of deleterious anions such as chlorides and sulfates.

There also does not appear to be any discrepancy between the early research by Romanoff (*1*) at the National Bureau of Standards (NBS) and the more recent occurrences of significant corrosion of pilings. Romanoff's statements concerning the absence of significant corrosion of pilings below the water table or in undisturbed soils are consistent with the more recent field data. Any problems with the Romanoff work appear to be associated with a misinterpretation or generalization of the conclusions of the original work. Romanoff may have inadvertently contributed to this problem by overly emphasizing the differences between behavior of piling below the water table or in undisturbed soils with the work

TABLE 1   Summary of indications of corrosion and techniques to assess corrosion of steel piling from data reported from various departments of transportation

State DOT	Indications of Corrosion	Corrosion Rate Measured y/n	Technique
Alberta	Pipe pile piers in lake/reservoir locations have shown signs of corrosion at the water line. Not able to coat piles below water line due to constant levels.	y	Excavate to expose piles and examine piles visually. Extract piles for visual investigation.
CA	Corrosion of steel pipe piles exhumed from structure in San Francisco Bay area (Attachment A).	y	Visual examinations and ultrasonic thickness measurements on piles to determine corrosion loss.
CT	Enclosed copies of references regarding corrosion.	y	Rely on research conducted by R.P. Long, University of Connecticut.
GA	Steel H-piles in brackish water.	y	Physical measurements.
IL	Sheet pile walls and piles supporting bridge abutments.	y	Aware of an FHWA Method.
IA	No major problems. Do experience corrosion of steel pile at groundline in pile bent type piers; Piles that are not encased in concrete or at the bottom of the concrete encasement.	y	Pulling piles that were installed for the purposes of checking on corrosion at specific bridge sites.
KS	Very few cases - web rusted through.	n	
MN	Corrosion at water line.	y	Measurements of loss of section using standard techniques.
NH	Corrosion just below 'stub' abutments when soil sloughs from below abutment, exposing steel piles.	n	There was a report and computer program referencing corrosion of metal culverts and predicting rates.
NY	No structure failures due to corrosion of steel piles. Piles driven in an industrial waste fill area showed 32% cross-section loss after 32 +/- years of service.	n	
OH	Just a few projects involving monotube-type capped pile piers.	n	
OK	Usually have section loss problems at water line, or at ground line. Frequently experience when fill under bridge seat of skeleton-type abutment settles/erodes, exposing steel piling. Runoff puts piling through wet/dry cycles, causing corrosion.	n	
Ontario	Have seen minor corrosion damage - visual observation only.	n	
PA	We have had some cases in limestone with water flow.	y	We are aware, but have not used.
TN	We have observed corrosion on steel piles that were exposed due to erosion beneath abutment capbeams. This is not a major problem.	n	
TX	Steel H-piling submerged in freshwater with high iron content.	n	
TX	Generally older bridges suffer at ground/water line due to lack of maintenance or continual attack over many years. Probably typical over rest of country.	y	We use visual methods with hand-held measuring devices.
WV	Settlement of fill under abutment exposed piling. Piling have shown extensive corrosion between soil and abutment.	n	
WS	Both H-Piles and cast-in-place piles have experienced serious corrosion in fresh water environments resulting from the activity of anaerobic sulfate-reducing bacteria.	n	
WY	Some corrosion and loss of section in high alkaline soils.	n	

on pipelines and other structures located entirely in disturbed soils. The fact of the matter is that a majority of pilings pass through some disturbed soils.

While the overall mechanism of corrosion of piling is thought to be well understood, attempts to correlate corrosivity of soil with variables such as pH, redox potential (Eh), resistivity, and the concentration of anions, have not met with much success. Typically, there is a lot of scatter in the data and correlation coefficients are low. This created a significant problem in selecting parameters for the Draft Recommended Practice that should be analyzed to assess corrosivity.

8

Specific areas of further research were identified from the state-of-the-art literature review and these areas were investigated by the inclusion of a large number of parameters in the Draft Recommended Practice and through laboratory soil analyses and field corrosion monitoring with corrosion probes at selected field sites. The specific areas of research addressed in the project are described in Appendix D and summarized below.

Soil Parameters

A large number of soil parameters were included in the Draft Recommended Practice for the characterization of the corrosivity of the soil. These include resistivity, pH, Eh, chloride concentration, sulfate concentration, CEC, and soil particle size. For the characterization of a site, these analyses would need to be performed on each soil stratum down to some distance below the water table. Even with such an extensive characterization, the predictive capability of models developed that include many of these parameters is poor. In addition, such an extensive analysis may inhibit engineers from using the Recommended Practice.

Accordingly, a better understanding was needed of the minimum parameters required to characterize the corrosivity of a site. For example, given the close relationship between soluble salt content of soils and resistivity, it may not be necessary to perform both types of analyses. The promising results of research studies by others on CEC also suggest that this parameter may greatly improve the predictive capabilities of soil models. With better models the specific parameters required to assess corrosivity and the ranges of those parameters associated with different levels of corrosivity can be more accurately defined.

Electrochemical Corrosion Assessment Techniques

Four electrochemical techniques were proposed in the Draft Recommended Practice for the evaluation of corrosivity; macrocell (galvanic) current, Eh, corrosion potential, and PR. Some of these techniques may be redundant (for example, Eh and corrosion potential) and the minimum number of electrochemical tests required to adequately characterize a site was unknown. The PR technique is normally used to assess rates of uniform corrosion, and it has not been established whether the technique provides useful information in the assessment of corrosivity where macrocell corrosion is the dominant corrosion failure mode. Furthermore, the best field probe designs and the relative value of laboratory versus field electrochemical tests have not been established.

Uniform Corrosion

As described above, the primary cause of significant corrosion of pilings is thought to be differential aeration cells.

Although little data were found in the literature search, it is possible that uniform corrosion could lead to high rates of attack in very low-pH soils (< 4), such as those containing some manufactured products. Accordingly, uniform corrosion was included as a possible failure mechanism in the Draft Recommended Practice.

Water Table

Two unresolved issues associated with the water table were identified from the literature search. One was the effect of the relative length of the pile above and below the water table on the magnitude of the galvanic effect. In one Army Corps of Engineer's report from the late 1960s, it was suggested that the ratio of the length of piling below the water table to that above the water table affects the maximum severity of attack. For instance, where the length of piling below the water table is large, the maximum corrosion is reduced. This behavior is reasonable for differential cell corrosion in that a large anode/small cathode reduces attack. A better understanding of this effect would help identify those piles that are most prone to severe corrosion.

The second issue is the maximum distance below the water table where galvanic corrosion is likely. Information on this is very limited, but the distance should be a function of soil resistivity, the kinetics of the oxidation and reduction reactions, and the potential difference between the anode and the cathode. It is important to establish this distance in order to limit the portion of each pile requiring examination or assessment.

Water Analysis

Groundwater analyses were included in the Draft Recommended Practice although it was unknown whether these analyses added substantially to the assessment of corrosivity. If the results of the soil analyses provide similar information, the elimination of the groundwater analyses would reduce the scope of the analyses required in the Recommended Practice.

DRAFT RECOMMENDED PRACTICE

A draft of the Recommended Practice was prepared earlier in the project in a format suitable for AASHTO "Recommended Practice" publication. This Draft Recommended Practice permitted future data collection at various field sites to be performed in a consistent manner and ensured that the appropriate data were collected that would answer the questions left unanswered by this research.

The draft of the Recommended Practice was provided in Appendix F of the interim report and was divided into three parts: *Part I—Environmental Conditions Causing Corrosion of Steel Piling, Part II—Design Considerations for New Pil-*

ing, and *Part III—Evaluation of Existing Steel Piling*. The Draft Recommended Practice was quite extensive and contained procedures and analysis techniques that were found to be redundant, based on the results of laboratory and field investigations. Results of laboratory and field corrosion tests conducted to evaluate the Draft Recommended Practice are given in the discussion to follow.

LABORATORY CORROSION TESTS

Laboratory Soil Cells

The purpose of performing tests with soil cells was to evaluate three electrochemical techniques used for measuring corrosion rates and to assess the relative value of laboratory versus field electrochemical testing. These three techniques consisted of measurements of corrosion potential, PR, and galvanic (macrocell) currents.

Romanoff (*1*) and Lee (*2*) indicated that corrosive soils generally have more negative potential values, based on either corrosion or redox potential measurements. The PR technique is normally used to assess rates of uniform corrosion over time. However, it has not been established whether the PR technique provides useful information in the assessment of corrosivity where macrocell corrosion is the dominant failure mode. For the case of macrocell corrosion, galvanic current measurements, performed with a corrosion probe, are converted to corrosion rates using Faraday's Law. Comparison of corrosion rates calculated from PR, galvanic current, and weight-loss measurements were used to evaluate the techniques and indicate the principal form of corrosion in a soil environment.

Polarization Resistance and Weight-Loss Measurements. In the first series of tests, PR and weight-loss measurements were performed with six soil cells to evaluate the PR technique and compare the corrosion rates calculated from both techniques. The cells were constructed using A36 steel plates and plexiglass cylinders with lids. All of the plates were initially grit-blasted with silica sand to a near-white condition to remove mill scale and establish a uniform surface. One weighed A36 steel coupon (1″ × 1″ × ¼″), having a 120-grit finish, was embedded vertically in each cell for the determination of weight loss. A graphite ring with an electrical connector was embedded near the top of the test cells to act as the counter electrode for the PR measurements. A copper/copper sulfate (Cu/CuSO₄) electrode was used as the reference electrode. The tops of the cells were sealed with tape and a rubber stopper to prevent moisture loss. The following soil cells were constructed:

1. −200 mesh bentonite with 24% moisture as deionized water,
2. Medium to fine sand with 12% moisture as deionized water,
3. −200 mesh bentonite with 24% moisture as 10 ppm NaCl water,
4. Medium to fine sand with 12% moisture as 10 ppm NaCl water,
5. CCT (field site) soil (#3, 6′–9′ depth) with 31% moisture, as-received, and
6. Buffalo (field site) soil (#6, 6′–7.5′ depth) with 12% moisture, as-received.

The sand and bentonite were tested at their optimum moisture contents as determined by the Proctor Test described in ASTM Method D 698 (*3*). The soils obtained from the CCT and Buffalo field sites were tested at their as-received moisture contents as determined by AASHTO Method T 265 (*4*) at 60°C. Photographs of the soil cells containing sand and bentonite are shown in Appendix E in Figure E1. Photographs of the soil cells containing soil from the Buffalo and CCT field sites are shown in Figure E2.

Corrosion potential and PR measurements, using a three-electrode PR technique, were performed weekly, for the first 6 weeks, and monthly thereafter, for a total exposure period of 85 days. Measurements were performed using ASTM Method G 59 (*5*). In this method, the specimen (A36 plate) potential was scanned between −20 mV (Cu/CuSO₄) and +20 mV (Cu/CuSO₄) of the free-corrosion potential at a scan rate of 0.17 mV/sec. The ensuing current was monitored as a function of potential. The tangent to the potential-current plot at the free-corrosion potential is the PR value.

Corrosion rates were calculated from both PR and weight-loss measurements and a comparison of the results was made. The PR values were converted to corrosion current using the Stern-Geary equation.

$$i_{cor} = \frac{\beta}{PR} \tag{1}$$

Where i_{cor} is the corrosion current in A/cm², β is the Tafel factor, and PR is the polarization resistance. The corrosion current values were converted to corrosion rates using Faraday's Law.

Weight losses of the coupons were measured using the interval weight-loss procedure described in ASTM Method G 1 (*3*). This technique involves the alternate descaling of the coupon in inhibited acid and weighing until the visible corrosion products are removed. Weight losses were then converted to corrosion rates by dividing the weight loss by the density, the coupon surface area, and the exposure time, and converting the units.

The results of the analyses of the sand and bentonite are shown in Table E1 in Appendix E. Analyses of the soils from the Buffalo and CCT field sites are given in Tables F1 and G1, in Appendix F and Appendix G, respectively. These data show the sand to have a pH of about 3, which suggests the

possibility for measurable uniform corrosion. The bentonite has a very low saturated resistivity, which is suggestive of very high corrosivity. The resistivity data from analysis of the CCT soil indicates mild corrosivity, whereas the resistivity data from analysis of the Buffalo soil indicates that it is corrosive to very corrosive. As discussed in Appendix D, pH and resistivity are factors that relate to corrosivity.

The results of the electrochemical tests are given in Tables E2 through E4 in Appendix E for the sand/bentonite, Buffalo soil, and CCT soil, respectively. Corrosion rates calculated from both PR and weight-loss measurements are shown graphically in Figure 1 and Figure E3 in Appendix E. These data show that the PR technique underestimated the corrosion rates compared with the rates calculated from weight-loss measurements. With the exception of the Buffalo soil, corrosion rates calculated by PR decreased over time. Although moisture loss over the exposure period may have been a factor in these results, the decrease in corrosion rate, with time, is not unusual. This decrease is often the result of formation of protective corrosion products or oxide films at the surface of the metal.

Weight-loss data from coupons exposed to both the sand and bentonite were similar and the corrosion rates were about 1 mil per year (mpy) whereas coupons embedded in the CCT and Buffalo soils exhibited corrosion rates of about 2 mpy and 3.7 mpy, respectively. The addition of 10 ppm NaCl to the bentonite and sand did not appear to have any significant effect on the corrosion rates. The low concentration of NaCl was added to ensure adequate conductivity for performing the electrochemical measurements. It should be noted, however, that the addition of 10 ppm NaCl in these tests would not be expected to affect the soil resistivity significantly.

Visual examination of the coupons immediately following the exposure period showed localized areas of rust on the coupons exposed to the sand and bentonite. Additionally, the coupon exposed to the sand exhibited some pitting. The coupon exposed to the CCT soil showed uniform rusting whereas the coupon exposed to the Buffalo soil showed more severe uniform corrosion.

Based on the results of these tests, the PR technique may have been effective in predicting trends in the corrosion rates over time although it underestimated the magnitude of the corrosion rates. It should also be noted that the PR values were not corrected for solution resistance prior to calculating corrosion rates. This correction would have increased the calculated corrosion rate to some degree.

Galvanic Current Measurements. In the second series of soil tests, three laboratory-sized corrosion probes were constructed and embedded in dissimilar soil strata or soil strata having different moisture contents for the purpose of measuring the magnitude and direction of galvanic current flow between the soil strata. A photograph of a typical probe is given in Figure E4 in Appendix E. In each of the three test cells, soil was compacted around the 6″ × 1″ probe in 1-liter

Teflon® jars such that four metal rings of the probe were embedded in each of two different types of soil. The following soil cells were constructed:

1. Sand with 12% moisture over bentonite with 24% moisture,
2. CCT soil (#3, 6′–9′ depth) with 31% moisture over saturated CCT soil (#3), and
3. Buffalo soil (#8, 9′–10.5′ depth) with 12.6% moisture, as-received, over Buffalo soil (#9, 12′–13.5′ depth) with 32% moisture, as-received.

Six of the rings on each probe were electrically coupled together. The top and bottom rings were left disconnected for corrosion potential and PR measurements under natural, freely corroding conditions. Galvanic current, PR, and corrosion potential measurements were made weekly for 1 month, and monthly thereafter, for a total exposure period of 113 days. Corrosion potential measurements were made with a high impedance voltmeter with respect to a $Cu/CuSO_4$ reference electrode. Galvanic current measurements were made between each electrically isolated ring and the remaining coupled rings using a Zero Resistance Ammeter (ZRA). Further details of the technique are discussed in Appendix M.

At the end of the exposure period, each of the probes was disassembled and the individual rings were descaled in accordance with the ASTM Method G 1, procedure C.3.1, and weighed. Corrosion rates were calculated from weight-loss data and compared with corrosion rates determined from PR measurements of the top and bottom rings, galvanic current measurements of the six coupled rings, and weight-loss measurements of each of the probe rings following the exposure period. The results of these tests were later compared with data generated from measurements taken at the three field sites with field corrosion probes.

The results of these electrochemical measurements are given in Tables E5, E6, and E7 in Appendix E for the sand/bentonite, Buffalo soil, and CCT soil, respectively. Corrosion rates calculated from both PR and weight-loss measurements, as a function of exposure time, are shown graphically in Figure E5 in Appendix E. These data show the following:

1. Corrosion rates, based on PR, were higher for rings exposed to the higher moisture content (bottom of the test cell) than the lower moisture content for corrosive soils, as determined from soil analyses.
2. Corrosion rates, based on PR, were slightly lower for the ring exposed to the higher moisture content (bottom of the test cell) than for the lower moisture content for low corrosivity soils (CCT soil), as determined from soil analyses.
3. Compared with the weight-loss technique, the PR technique overestimated corrosion rates for rings at the bot-

*Figure 1.   Corrosion rates calculated from PR and weight-loss (WL) measurements for A36
steel tested in various environments for 85 days in the laboratory.*

tom of the cells, but approached the corrosion rates for rings at the top of the soil cells in the Buffalo and CCT soil environments.

Figures E6 through E8 show the galvanic current, as a function of depth, measured with each of the lab probes. A positive galvanic current is cathodic and a negative galvanic current is anodic. Macrocell corrosion is indicated by a negative galvanic current flow from a ring. These data show that galvanic current flow between the dissimilar soil layers was observed in each of the three tests. The magnitude of the cur-

rents generally increased over time for probes in corrosive soils, with the exception of the initial and final measurements. The current magnitudes were much lower and continued to decrease for the probe in the less corrosive CCT soil. Tables E5 through E7 compare corrosion rates calculated from galvanic current, PR, and weight-loss data. The similarity between corrosion rates calculated from galvanic current and weight-loss measurements for the three deepest rings in the sand/bentonite and Buffalo soil cells suggests that macrocell corrosion was the primary form of corrosion in these two environments.

12

Figures E9 through E11 show corrosion potential data for the top and bottom probe rings in each of the three test cells. Although there were no significant trends in potential measurements over time for any given ring, the potential measurements of the top and bottom ring in any given test cell did identify the anodic and cathodic areas. In each case, the probe ring at the bottom of the test cell had the more negative potential and served as the anode, whereas the top ring had the more positive potential and served as the cathode.

Potentiodynamic Polarization Tests. In the third series of soil tests, duplicate soil cells were constructed with sand, bentonite, and soil from each of the three field sites for potentiodynamic polarization testing and the determination of Tafel constants. The Tafel constants are required to convert the PR data to corrosion rate.

A Tafel factor of 0.026 was initially used in all of the corrosion rate calculations from PR data. This value is typical of carbon steel in a soil environment, based on information found in the literature by Long (6), Fontana (7), and Treseder (8). However, analysis of much of the data showed the PR technique underestimated corrosion rates by at least an order of magnitude, compared with the rates calculated from weight-loss measurements when the Tafel factor of 0.026 was used.

In these tests, the laboratory cells used A36 plates and plexiglass cells with lids, as described above, with the exception that no coupons were embedded in the soil. The soils were allowed to sit at ambient temperature for 7 days prior to performing anodic and cathodic potentiodynamic polarization tests. The specimen potential was scanned from -50 mV to $+300$ mV of the free-corrosion potential for the anodic scan and $+50$ mV to -300 mV of the free-corrosion potential for the cathodic scan. All scan rates were 0.17 mV per sec. The Tafel constants, β_a and β_c, are the anodic and cathodic Tafel slopes, respectively. These slopes were taken directly from the polarization curves by drawing tangents to the curves at over-potentials of $+75$ and -75 mV from the free-corrosion potential. The Tafel factor (β) was calculated for the Stern-Geary equation.

$$\beta = \frac{(\beta_a)(\beta_c)}{2.3(\beta_a + \beta_c)} \qquad (2)$$

Corrosion currents were calculated by dividing the Tafel factor by PR, in ohms-cm^2. The corrosion currents were converted to corrosion rates using Faraday's Law.

The polarization curves for each of the soils are given in Figures E12 through E16 in Appendix E. Table E8 shows the Tafel slopes and factors obtained from each of the polarization curves. These data show the anodic and cathodic Tafel slopes to be considerably different than the 0.120 volts/decade (Tafel factor of 0.026) described in the literature. Larger Tafel slopes generated larger Tafel factors. The almost double Tafel factors served to almost double corrosion rates calculated from PR measurements. Thus, all of the

corrosion rate data, calculated from PR, presented in this report, used Tafel factors from the actual polarization curves.

FIELD INVESTIGATIONS

The Draft Recommended Practice was applied in the field at three sites having varying degrees of corrosivity. These sites, and their anticipated corrosivity, were as follows:

1. Buffalo, New York (Buffalo)—Corrosive,
2. CC Technologies (CCT) in Dublin, Ohio—Non-corrosive, and
3. LaGuardia Airport (LaGuardia) in New York, New York—Non-corrosive.

Soil was sampled at each of the three field sites and groundwater was sampled at two of the sites and analyzed to characterize their corrosivity.

The soil parameters included resistivity, pH, soluble chloride and sulfate concentration, CEC, moisture content, and particle size distribution. Water parameters included pH, conductivity, chloride, sulfate, and bacterial types and counts. For characterization of the field sites, these analyses were performed on each soil stratum from the surface to about 3 ft below the water table. The purpose of the investigation was two-fold. First, all of the tests were performed to determine which, if any, could be eliminated and still be able to adequately assess soil corrosivity. For example, given the close relationship between resistivity and soluble salt concentration, all three tests were thought not to be necessary. Secondly, the data were used in the prediction modeling task of the program to more accurately define the specific parameters required to assess corrosivity and the ranges of those parameters associated with different degrees of corrosivity.

A field corrosion probe was devised and installed at each of the sites, at a depth to straddle the water table, for the purpose of measuring corrosion potential, Eh, PR, and galvanic current measurements. The total exposure periods ranged from 49 days to 120 days. The objective of this portion of the work was to provide input for modification of the Draft Recommended Practice using a two-fold approach. First, the Draft Recommended Practice was applied to determine its workability and feasibility under actual field conditions. Secondly, electrochemical measurements, made with field corrosion probes, were used to supplement the characterization of soil and groundwater corrosivity of the field sites and provide input to the statistical data analysis and modeling efforts.

A schematic of the probe is shown in Figure 2. One prototype and three additional probes were constructed with black iron pipe and polyvinyl chloride (PVC) pipe. A sample of the steel purchased for the probes was analyzed to ensure that the material met specifications for K02600 (A36) steel. Table 2 gives the results of the analysis and the chemical specifications for A36 steel. These data show that the steel met the specifications for A36 steel.

Figure 2. Schematic of field corrosion probe.

All of the steel was initially grit-blasted with silica sand to a near-white condition to remove mill scale and establish a uniform surface. For each probe, eight, 10.16-cm (4-in.) lengths of pipe (rings) were cut and deburred to serve as working electrodes. These rings were then drilled, tapped, cleaned, and weighed. Electrical lead wire was attached to a screw in the inside of each ring and threaded up through an inner steel pipe (for support and strength) during assembly. The inner and outer steel pipes were electrically isolated from each other with an inner, grooved PVC pipe (insulator). The 40.6-cm (16-in.) top and bottom sections, each comprised of four steel rings isolated with PVC rings and rubber gaskets, were constructed separately and connected to the middle reference electrode segment with unions. A Cu/CuSO₄ electrode was mounted in this middle segment to serve as the reference electrode. A platinum electrode was also included for measurement of Eh. A case-hardened tip was connected to the bottom of the probe and segments of pipe were used as extensions to allow placement of the probe rings at the desired depth. The overall corrosion probe measured approximately 4.2 cm (1.66 in.) in diameter and 1.27 meters (50 in.) in length when fully assembled. A special adapter was constructed to fit on the end of the extensions to allow the probe to be driven by a rotary hammer-drill.

Corrosion potentials were measured with each ring with respect to a Cu/CuSO₄ electrode. The potentials of the rings also were measured with respect to a platinum electrode. The

TABLE 2 Analysis of steel used in corrosion probes and specification for A36 (K02600) steel

Element	Inner Steel Pipe	Outer Steel Pipe	A36
Carbon, C	0.19	0.19	0.26 Max
Manganese, Mn	0.35	0.42	
Phosphorous, P	0.022	0.018	0.04 Max
Sulfur, S	0.006	0.013	0.05 Max
Silicon, Si	0.014	0.013	
Copper, Cu	0.039	0.023	0.20 Max
Tin, Sn	0.007	0.002	
Nickel, Ni	0.016	0.011	
Chromium, Cr	0.028	0.023	
Molybdenum, Mo	0.013	0.014	
Aluminum, Al	0.038	0.061	
Vanadium, V	0.001	0.002	
Niobium, Nb	0.000	0.000	
Zirconium, Zr	0.000	0.001	
Titanium, Ti	0.001	0.001	
Boron, B	0.0001	0.0001	
Calcium, Ca	0.0003	0.0004	
Cobalt, Co	0.001	0.002	
Lead, Pb	0.00	0.00	

14

PR measurements were taken both above and below the water table to measure the instantaneous rate of corrosion. For the PR measurements, one ring served as the working electrode, an adjacent ring served as the reference electrode, and the two rings on either side of these served as the counter electrode. Solution resistance corrections of the PR measurements were not performed at any of the field sites, which may account for some variability between corrosion rates calculated from PR as compared with rates calculated from weight-loss measurements. Galvanic current measurements were made to identify the possibility for macrocell corrosion.

The purpose of having eight separate rings as working electrodes in the probe was to enable electrochemical measurements to be performed at various depths. Each of the rings, having different corrosion potentials as a result of changing soil chemistry with depth, generates a current flow (galvanic current) when they are coupled together. In the galvanic current measurements, each of the rings is uncoupled (isolated) in succession and the current flow is measured between each isolated ring and the remaining coupled rings using a ZRA. The magnitude and direction of the current flow indicate which rings experience accelerated corrosion because of galvanic coupling and which rings experience a reduction in the corrosion rate as a result of galvanic coupling. The coupled rings serve to simulate a pile extending vertically through the soil. Uncoupling of the various rings allows characterization of specific isolated 10.16-cm (4-in.) areas of the simulated pile as to which are the anodic and cathodic sites that form the basis for macrocells. For the galvanic current data presented in Appendixes F, G, and H, for the Buffalo, CCT, and LaGuardia sites, respectively, a positive galvanic current is cathodic and a negative galvanic current is anodic.

Each of the measurements described above was obtained initially and at the end of the exposure period at the Buffalo and LaGuardia sites and interim measurements were taken at the CCT site. Total probe exposure periods ranged from 49 days to 120 days in this program. Upon removal, the probes were wiped clean and coated with oil to prevent rusting during transport to the laboratory. Thereafter, the probes were disassembled and the rings were cleaned in a chloride-free detergent, rinsed, and immediately dried with acetone to prevent flash rusting. The cleaned rings were weighed and optically examined. If warranted, the rings were descaled in accordance with ASTM Method G 1 (3), Designation C.3.1. In this procedure, specimens are alternately weighed and descaled until there is no visible evidence of corrosion products or deposits. True weight losses are converted to corrosion rates in mpy by dividing the weight loss by the density, the specimen surface area, and the exposure period and converting the units. Following the descaling procedure, the specimens were re-examined optically at 30X magnification. Corrosion rates calculated from weight-loss measurements were compared with corrosion rates calculated from both the PR and galvanic current measurements made during the field

exposure. The corrosion rate data from these tests were also compared with corrosion rate data obtained from the laboratory testing, where applicable. All of the information from this field work provided input for the regression model developed in Task 5.

The following paragraphs discuss the data from analyses of the soil and groundwater samples obtained at the three sites and the results of the field electrochemical measurements.

Buffalo, New York

Soil and Water Data. Soil and groundwater samples were collected from the site in Buffalo, New York, in July 1996. The site was selected on the basis of prior soil boring information that indicated the presence of mixed rubble fill and the fact that the pile cap is above the water table. In many instances identified through our literature search, mixed fill was shown to be potentially very corrosive.

The site location is shown in Appendix F in Figures F1 and F2. Elevation drawings of the structure are given in Figures F3 and F4. Samples were collected with a 7.6-cm (3-in.) diameter split spoon through a 10.2-cm (4-in.) cased hole to a depth of 5 m (16.5 ft). One problem was encountered during soil collection at the Buffalo site. Casing had to be run due to hole collapse after soil had been sampled from 2.7 m to 3.2 m (9 to 10.5 ft). Depth measurements following the casing operation showed the boring to be filled with about 1 m (3 ft) of soil. The extra meter of soil was circulated from the hole with air. Thereafter, no samples could be obtained from 3.2 to 3.6 m (10.5 to 12 ft) which suggested that air circulation may have removed too much soil.

The soil was nonhomogeneous and primarily composed of gravel-sized particles of brick, glass, wood, slag, and cinders. The pH of the soil was measured in the field using ASTM Method G 51 (3). In this method, a pH electrode is placed in direct contact with the soil and the pH is read directly from the pH meter. The 2-cm (0.75-in.) average particle size made direct electrode contact very difficult and yielded unstable pH values. Additionally, the particle size prohibited as-received resistivity measurements in the field. The soil and groundwater samples were brought back to the laboratory and analysis was begun within 48 hours of sampling.

Results of the analyses of the soil and groundwater are given in Tables F1 and F2, respectively, in Appendix F. Figures F6 and F7 show graphical comparisons of the soil data. They show the soil, in general, to have pH values between 7 to 9, which indicate neutral to slight alkalinity. Saturated soil resistivity of all soil strata below 58 cm (23 in.) was less than 100 ohm-cm, which indicates that the soil is very corrosive, based on guidelines taken from a text for the Appalachian Underground Corrosion Short Course (9). The soluble chloride and sulfate contents of the soil were quite high, as expected, given the inverse relationship between resistivity and salinity.

The data for the groundwater were very similar to the data obtained for the deepest soil sampled. For example, the water had a chloride and sulfate content of 327 mg/L and 91 mg/L, respectively, whereas the soil showed soluble chloride and sulfate contents of 398 mg/kg and 96 mg/kg, respectively. Greater than 10,000 aerobic and iron-related bacteria were counted per milliliter of water. Other bacteria culture tests showed between 100 to 1000 acid-producing bacteria and 1000 to 10,000 general anaerobic bacteria per milliliter of water. The presence of bacteria may exacerbate corrosivity.

In summary, the presence of low resistivity, disturbed, mixed fill suggests that soil at the Buffalo site is highly corrosive. The presence of large amounts and types of bacteria in the groundwater may serve to exacerbate corrosion of the steel.

Field Measurement Data. A field corrosion probe was installed at the Buffalo site on October 15, 1996. The probe was inserted into the ground to a depth sufficient to straddle the water table at a depth of about 1.5 m (60 in.). Initial corrosion potential, PR, and galvanic current measurements were made within 1.5 hours of placement. The probe remained at the site for 49 days, at which time it was retrieved because of a scheduled demolition of the overhead bridge deck. Prior to removal of the probe, galvanic measurements were made on the electrically coupled rings. Following the galvanic measurements, the individual rings of the probe were uncoupled (isolated) and corrosion potential measurements were made immediately following uncoupling and again 30 minutes later to look at the effects of depolarization. Thereafter, PR measurements were made on rings located above and below the water table. Table F5 summarizes the results of the electrochemical measurements made with the field corrosion probe.

Corrosion potential data, measured with respect to Cu/CuSO$_4$ and Pt, initially, after 49 days, and at 49 days after 30 minutes of depolarization, as a function of depth, are shown graphically in Figures F8 through F10 and Figures F12 through F14, respectively. Figures F11 and F15 summarize these potentials with respect to Cu/CuSO$_4$ and Pt, respectively, as a function of depth and time. These data show that corrosion probe rings located below the water table had more negative potentials than probe rings located above the water table. This difference in potential is expected because oxygen levels are lower in soils beneath the water table. Data in Figures F11 and F15 show that measured potentials were lower at the end of the exposure period compared with initial measurements, and measurements following 30 minutes of depolarization showed negligible changes. Based on information found in the literature, steel in more corrosive soils has more negative potential value at or near the water table. Soil resistivity data for this site also suggested high corrosivity.

Comparison of corrosion potentials measured with respect to Cu/CuSO$_4$ and Pt electrodes over the exposure period is given in Figures F16 and F17. These data show relatively consistent potential differences between the two electrodes at each individual time period, and both electrodes appeared to indicate the same trend in potential over time. However, the magnitude of the potential difference between the two electrodes changed over time. Additionally, potential readings in the field with respect to Pt tended to drift toward zero. The drift in potential measurement may have been attributed to a very high impedance of the platinum electrode. A comparison of potential data measured with respect to Cu/CuSO$_4$ and Pt are discussed in more detail in the section titled "Comparative Analyses."

Comparison of corrosion potentials from lab soil cell data given in Table F3 with potential data from the field corrosion probe given in Table F5 show that more negative potentials were recorded in the laboratory. The more negative potentials observed in the laboratory tests may be attributed to possible reduction in oxygen content from sealing the cell to prevent moisture loss.

Figures F18 and F19 in Appendix F show galvanic current data initially and after 49 days of exposure, respectively. Figure F20 graphically summarizes the changes in galvanic current at these times as a function of depth. These data show varying current values in both magnitude and direction. Macrocell corrosion is indicated by a negative galvanic current flow from a ring. As discussed in Task 2, macrocell development is of prime concern from the standpoint of piling corrosion. Furthermore, the data in Figure F20 shows an increase in galvanic current after 49 days of exposure for probe rings located in the vicinity of the water table. This behavior may indicate that time is required following insertion of the probe, for the development of stable macrocells.

Corrosion rates were calculated from field probe PR, weight loss, and galvanic current measurements. Figure F21 graphically compares these corrosion rates as a function of probe ring depth. These data show that the PR technique underestimated corrosion rates, but predicted an increase in corrosion rate over time. The technique further predicted a higher corrosion rate for the ring that was located above the water table during the exposure. These data further show that galvanic current made a minor contribution to the total corrosion rate, as determined from weight loss for the ring located at that particular depth.

These data were correlated with data obtained from laboratory soil cells and the results are exhibited graphically in Figure F22. These data show that corrosion rates calculated from field PR measurements more closely approximated corrosion rates calculated from weight-loss data. Furthermore, corrosion rates calculated from field probe weight-loss data were higher, albeit similar, than rates predicted in the laboratory test cells. Galvanic current measurements were not made in the laboratory in the soil depth indicated in Figure F22. However, if corrosion rates calculated from galvanic measurements are compared, in general, between the lab and field probes (Tables F4 and F5), the lab probe data

suggests that galvanic (macrocell) corrosion made a significant contribution to the total corrosion rate, calculated from weight-loss measurements. On the other hand, the field probe data showed macrocell corrosion to be insignificant to the total corrosion rate at the Buffalo site. Additionally, corrosion rates calculated from weight loss were similar for both the lab and field probe rings, and visual examination of both sets of rings showed uniform corrosion.

CC Technologies in Dublin, Ohio

Soil and Water Data. Soil and groundwater samples were collected from CC Technologies' newly constructed facility in Dublin, Ohio, in August 1996. The site was selected for two reasons. First, the facility was less than 1 year old and the soil was disturbed natural soil. Disturbed natural soil is relatively less aggressive than manufactured products, but can be porous, allowing diffusion of oxygen to a pile. Secondly, the site allowed the researchers to experiment with a new soil sampling device and corrosion probe placement techniques as well as to permit monthly monitoring of a field corrosion probe without having to incur travel expenses.

Soil and groundwater samples were collected on August 5, 1996, with a 3-cm (1.2-in.) diameter subsurface probe. A schematic of the soil probe is shown in Figure G1 in Appendix G. Soil samples were taken to a depth of 2.7 m (9 ft) and water was sampled at about 1.3 m (51 in.).

The soil was homogeneous sand with some gravel and fines. The results of the analyses of the soil and groundwater are given in Tables G1 and G2, respectively, in Appendix G. Figures G2 and G3 show graphical comparisons of the soil data. These data show the soil to have pH values between 6 and 7.5, which indicate slightly acidic to neutral conditions. Saturated soil resistivity of all soil strata were between 1980 and 2000 ohm-cm, which is indicative of corrosive to mildly corrosive soil. Soluble chlorides were found to be less than 25 mg/kg and soluble sulfates were less than 60 mg/kg.

The data for the groundwater, shown in Table G2, were very similar to the data obtained for the deepest soil sampled. For example, the water had a chloride and sulfate content of 12 mg/L and 62 mg/L, respectively, whereas the soil showed soluble chloride and sulfate contents of 6 mg/kg and 56 mg/kg, respectively. Greater than 10,000 aerobic and iron-related bacteria were counted per milliliter of water. Other bacteria culture tests showed between 100 to 1,000 acid-producing bacteria and 1,000 to 10,000 general anaerobic bacteria per milliliter of water. Additionally, up to 10 sulfate-reducing bacteria were detected per milliliter of water.

In summary, the presence of intermediate resistivity, disturbed, natural fill suggests the possibility of mild, uniform corrosion. The presence of large amounts and types of bacteria in the groundwater may serve to exacerbate the corrosion of steel.

Field Measurement Data. A field corrosion probe was placed at the CCT field site on October 2, 1996. The probe was inserted into the ground to a depth sufficient to straddle the water table (a depth of about 1.6 m [62 in.]). Initial corrosion potential measurements were made within 3 hours of probe placement and again 24 hours after placement. PR and galvanic current measurements were also made 24 hours after probe placement. Corrosion potential and galvanic current measurements were made monthly for 4 months, and PR measurements were made after 92 days and at the end of the 120-day exposure period. Similar to the field measurements at the Buffalo site, corrosion potential measurements were made 1 hour after uncoupling the probe rings to look at the effects of depolarization. Table G5 in Appendix G summarizes the results of the electrochemical measurements made with the field corrosion probe.

Corrosion potential data, measured with respect to Cu/CuSO₄ and Pt, throughout the exposure period, as a function of depth, are shown graphically in Figures G4 through G9 and G11 through G14, respectively. Figures G10 and G15 summarize these potentials with respect to Cu/CuSO₄ and Pt, respectively, as a function of depth and time. These data show fewer negative potentials than those measured at the Buffalo site and the potentials were considerably less negative after 24 hours. Additionally, potential values were very similar for probe rings placed both above and below the water table and no depolarization was observed in the later measurements. The fewer negative potential values and similarity with depth may have been due to the near proximity or change in the water table over the exposure period or the presence of higher oxygen levels in the sandy soil above the water table. The potential shift in a more positive direction with time may have been due to the development of oxide films at the metal surface. These trends in corrosion potential are suggestive of a low corrosivity environment.

Comparison of corrosion potentials from lab soil cell data given in Tables G3 and G4 with potential data from the field corrosion probe given in Table G5 show that considerably more negative potentials were recorded in the laboratory. More negative potentials are suggestive of higher corrosivity, and corrosion rates calculated from weight-loss measurements on the laboratory probe rings and soil cell coupon were much higher than rates calculated from weight-loss data from the field probe rings.

Comparison of corrosion potentials measured with respect to Cu/CuSO₄ and Pt electrodes over the exposure period are given in Figures G16 and G17. As at the Buffalo site, comparison of the potential measurements showed consistent differences during any particular measurement time frame, but the magnitude of the potential differences changed over time. Additionally, potential readings with respect to Pt in the field tended to drift toward zero.

Figures G18 through G22 in Appendix G show the galvanic current data obtained from field measurements with the corrosion probe after 24 hours, 28 days, 56 days, 92 days, and

120 days of exposure, respectively. Figure G23 graphically summarizes the change in galvanic current at these times as a function of depth. These data show varying current values in both magnitude and direction. In Figure G18, the negative galvanic currents shown for the third and fourth probe rings were not typical for steel above the water table. These negative currents were thought to be from a temporary rise in the water table from probe placement or a layer of soil that more readily held moisture than the adjacent layers. As seen in Figure G20, the current direction for these two probe rings reversed. Data in Figure G23 clearly show a decrease in galvanic current with time, which is further suggestive of a low corrosivity environment.

Corrosion rates were calculated from field probe PR, weight loss, and galvanic measurements. Figure G24 graphically compares these corrosion rates as a function of probe ring depth. These data show that the PR technique overestimated corrosion rates, but predicted a decrease in corrosion rate over time. The technique further predicted similar corrosion rates for the rings located above and below the water table during the exposure. These data also show that galvanic current made a very minor contribution to the total corrosion rate, as determined from weight loss for the ring located at that particular depth.

These data were correlated with data obtained from laboratory soil cells and the results are exhibited graphically in Figure G25. These data show that corrosion rates calculated from field PR measurements more closely approximated field corrosion rates calculated from weight-loss data. In general, all of the laboratory measurements overestimated corrosion rates as compared with rates measured with the field probe. Corrosion rates calculated from galvanic currents show that, for the lab probe, macrocell corrosion made some contribution to the total corrosion rate, calculated from weight-loss data. On the other hand, macrocell corrosion was insignificant to the total corrosion rate of the field probe rings. Visual examination of the probe rings exposed in the laboratory soil cells showed uniform corrosion whereas field probe rings showed no apparent corrosion deposits or attack.

LaGuardia Airport in New York, New York

Soil and Water Data. Soil samples were collected in October 1996 from a site at LaGuardia Airport in New York, New York. This site was chosen by Mr. Victor Chaker, the Port Authority of New York and New Jersey, on the basis of the contents of a previous boring report. The Boring Report, dated February 6, 1996, for Boring No. B-6A, indicated brown medium- to fine-grained sand with some gravel, cobbles, glass, and wood. Thus, it was speculated that the mixed fill may be corrosive.

Soil samples were collected on October 22, 1996, with a 3-cm (1.2-in.) diameter subsurface probe. The site was located within 1 m of piling near the abandoned exit from the central terminal parking garage. The sampling site was located less than 30 m (100 ft) away from Boring No. B-6A. Duplicate soil samples were taken 76 cm (30 in.) apart to a depth of 3.6 m (12 ft). Duplicate samples were obtained for two reasons: first, to ensure a sufficient sample size for testing purposes and second, to evaluate the effects of sample containment and shipping delays on pH, moisture, and resistivity. The results of this study are discussed in the section "Comparative Analyses" and the data are presented in Appendix I.

The soil appeared to be primarily medium to fine sand with very small amounts of gravel. On-site pH and as-received measurements were only made on the second set of samples. The first set of samples remained encased in sampling tubes to study the effects of containment and shipping delays.

The pH of the soil samples was measured in the field using ASTM Method G 51 and the values ranged from 6.0 to 7.8, indicating slightly acidic to neutral conditions. As-received resistivity measurements, using ASTM Method G 57,(3) were made on site and showed resistivities greater than 20,000 ohm-cm for soil above the water table. For soils sampled below the water table, the resistivities ranged from 4,000 to 9,000 ohm-cm. Thus, the as-received resistivities indicated low corrosivity at this site. The samples were driven back to the laboratory over a 4-day period for further analysis. A sample of the groundwater could not be obtained because of continual collapse of the borehole at the water table.

Results of the laboratory soil analyses are given in Table H1 in Appendix H. Figures H1 and H2 show graphical comparisons of the soil data. These data show soil pH to be between 6.1 and 6.9. As-received resistivity values ranged from 37,000 to 83,000 ohm-cm for soils sampled above the water table and values between 1,600 and 12,000 ohm-cm for soils sampled below the water table. When the soils were saturated, the resistivities ranged from 6,600 to 18,000 ohm-cm for soil sampled above the water table and 1,300 to 11,000 ohm-cm for soil sampled below the water table. These resistivity values are indicative of low to mild corrosivity although one corrosive area was noted between a depth of 3 to 3.2 m (10 ft to 10.5 ft). The difference in resistivity noted between soils sampled above and below the water table would seem to suggest that there would be a difference in salinity between these zones. However, soluble chlorides were below the detection limits of 10 mg/kg in the samples. Soluble sulfates were also low (less than 70 mg/kg) with the exception of the corrosive strata, which had a soluble sulfate content of 815 mg/kg. The difference in resistivity may be due to the difference in moisture content of the soil, for example, solution resistance. Moisture content for soils sampled above the water table were less than 10 percent whereas moisture contents ranged from 17 percent to almost 33 percent for soils sampled below the water table.

In summary, the high soil resistivities suggest low soil corrosivity with the exception of the strata at a depth of 3 m.

Field Measurement Data. A field corrosion probe was placed into the first borehole (of two) at the LaGuardia field site on October 24, 1996. The probe was inserted into the ground to a depth sufficient to straddle the water table at a depth of about 2.3 m (92 in.). Initial corrosion potential and PR measurements were performed within 0.5 hours of placement and again 18 hours after placement. Galvanic current measurements were made 18 hours after probe placement. The probe remained at the site for 103 days, at which time it was retrieved because of time constraints involved with the completion of the research program. Prior to removal of the probe, galvanic measurements were made on the electrically coupled rings. Following the galvanic measurements, the individual rings of the probe were uncoupled (isolated) and corrosion potential measurements were made immediately following uncoupling, and again 30 minutes later, to see the effects of depolarization. Thereafter, PR measurements were made on rings located above and below the water table. Table H2 in Appendix H summarizes the results of the electrochemical measurements made with the field corrosion probe.

Corrosion potential data, measured with respect to $Cu/CuSO_4$ and Pt, after 0.5 hours, 19 hours, 103 days, and 103 days after 30 minutes of depolarization, as a function of depth, are shown graphically in Figures H3 through H6 and Figures H8 through H11, respectively, in Appendix H. Figures H7 and H12 summarize these potentials with respect to $Cu/CuSO_4$ and Pt, respectively, as a function of depth and time. These data are similar to the Buffalo potential data in that more negative potentials were measured with probe rings exposed below the water table. Potentials measured with respect to $Cu/CuSO_4$ drifted in the negative direction with time whereas potentials measured with respect to Pt drifted in the positive direction.

A comparison of corrosion potentials measured with respect to $Cu/CuSO_4$ and Pt electrodes over the exposure period is given in Figures H13 and H14. These data show highly inconsistent potential differences between the two electrodes at each individual time period although both electrodes appeared to indicate relative trends in potential with depth. Potential readings in the field with respect to Pt were not very stable and tended to drift toward zero. Unlike at the Buffalo and CCT field sites, the magnitude of the potentials measured with respect to $Cu/CuSO_4$ and Pt at the LaGuardia site drifted in opposite directions with time.

Figures H15 and H16 in Appendix H show galvanic current data after 19 hours and 103 days of exposure. Figure H17 graphically summarizes the changes in galvanic current at these times as a function of depth. These data show varying current values in both magnitude and direction in the vicinity of the water table and at a depth between 2.7 and 2.9 m (109 and 114 in.). Furthermore, the galvanic currents increased over time, which suggested macrocell corrosion.

Corrosion rates were calculated from field probe PR, weight loss, and galvanic current measurements. Figure H18 graphically compares these corrosion rates as a function of probe ring depth. For the ring located below the water table, these data show that the PR technique overestimated the corrosion rate and predicted an increase in this rate over time. For the ring located above the water table, these data show that the PR technique underestimated the corrosion rate and predicted a decrease in this rate over time. Corrosion rates calculated from weight-loss data showed that the ring above the water table had a slightly higher corrosion rate than the ring located below the water table. These data further show that galvanic current made a major contribution to the total corrosion rate, as determined from weight loss for the ring located below the water table. Comparison of corrosion rates calculated from galvanic current and weight-loss data in Table H2 show that the rates were essentially identical for the fifth and eighth probe ring. These data suggest that macrocell corrosion was the primary form of corrosion at those depths, whereas uniform corrosion was the primary form of corrosion for the remaining probe rings. The discrepancy between corrosion rates calculated from PR and weight loss for the ring below the water table may have been due to the significant contribution of macrocell corrosion.

Visual examination of the field probe rings showed all eight to have undergone uniform corrosion. Rings that were located above the water table appeared, in general, to have localized areas of more severe attack than rings located below the water table. Corrosion rates calculated from weight loss also indicated slightly higher corrosion rates for rings positioned above the water table. Macrocell corrosion suspected as the primary form of corrosion for the fifth and eighth rings could not be confirmed from visual examination. Longer-term exposure periods may be necessary to differentiate macrocell and uniform corrosion.

Comparative Analyses

Data comparisons were made to evaluate the following:

1. Soil pH measurements by three different test methods,
2. Effects of shipping delays on soil pH and as-received resistivity,
3. Effects of sample containment on soil moisture, pH, and as-received resistivity,
4. Corrosion potentials measured with respect to $Cu/CuSO_4$ and Pt reference electrodes, and
5. Corrosion rates calculated from electrochemical and gravimetric data obtained from laboratory soil cells with data from field corrosion probes.

Figures I1 through I3 in Appendix I show the effects of test methodology on soil pH for soils sampled at the Buffalo, CCT, and LaGuardia sites, respectively. These data show that soil pH measured directly with a pH probe (ASTM Method G 51) are typically one pH unit lower than pH measured in a

1:1 soil:water slurry (ASTM Method D 4972). However, the ASTM Method G 51, *Standard Test Method for pH of Soil for Use in Corrosion Testing*, relies on a sufficient amount of moisture being present to achieve stable, accurate pH measurements; thus it is not reliable for coarse-textured soil such as that sampled at the Buffalo site (Figure I1).

The data in Figures I1 through I3 further show that pHs measured in a soil:0.01 M $CaCl_2$ slurry are typically 0.5 pH units lower than pHs measured in a soil:deionized water slurry. These trends in the data are in good agreement with information given in the literature. The ASTM Method G 51 tends to overestimate the activity of hydrogen ions in solution due to the excessive soil-particle-pH probe contact. Thus, a lower pH would be expected using the ASTM Method G 51 than pH measured by other methods. Furthermore, information in the literature indicates that a slight decrease in pH is expected when the soil slurry contains calcium chloride as compared with the pH obtained using deionized water because of the displacement of some of the exchangeable aluminum, which then hydrolizes in solution (*1*). Based on these observations, the Recommended Practice in Appendix K (not published here) suggests that pH be determined on-site, using the ASTM Method G 51, if the soil texture is primarily sand-size or finer and if the sampling procedure is amenable to on-site testing and that ASTM Method D 4972 be used for primarily gravel-sized soils.

Figures I4 and I5 show the effects of shipping delays on soil pH and as-received resistivity, respectively. For this comparison, pH and resistivity measurements were performed in the field on soil sampled at the LaGuardia site. These samples were subsequently double-bagged in plastic bags and returned to the laboratory. The pH and resistivity measurements were performed on these same samples 4 days later using the same test methods. The pH data in Figure I4 shows that pH values were lower after 4 days for soil sampled deeper than 111.7 cm (44 in.) and generally higher for soil sampled less than 111.7 cm (44 in.). However, the change in the pH values in these instances was typically 0.5 pH units or less.

The data in Figure I5 show that, in most cases, resistivity increased after 4 days. This increase appeared to be more pronounced in soil sampled at shallower depths having lower moisture contents. This trend was expected because of slight moisture loss over time. Based on these observations, the Recommended Practice recommends that samples be tested on-site for pH and as-received resistivity and then stored in glass jars to reduce the variability in subsequent measurements. The Practice further recommends that samples be shipped to the laboratory within 1 to 2 days.

Figures I6 through I9 show the effects of sample containment on soil moisture, pH, and as-received resistivity. For these comparisons, duplicate soil samples were taken 76 cm (30 in.) apart at the LaGuardia site with the subsurface soil probe to a depth of 3.6 m (12 ft). The first soil samples were retained in the plastic probe liner. The encased

soils were capped, labeled, and transported back to the laboratory over a 4-day period. The second set of samples, taken 76 cm (30 in.) away, was removed from the plastic liner, tested for pH and as-received resistivity, and subsequently double-bagged in plastic bags. These soils were transported back to the laboratory over the same period. Once received at the laboratory, sample depths were determined on what visually appeared to be distinct layers at the time of sampling. Thereafter, percent moisture, pH, and resistivity measurements were determined.

Although these data really compare two different soils sampled about 76 cm (30 in.) apart, the soils appeared to be fairly homogeneous. Figure I6 shows that moisture contents were fairly similar for soils above the water table. The variability in moisture content below the water table may be attributed to water drainage as the soil was sampled. In Figure I7, no real correlation could be seen in the pH values between the two types of shipping containers. However, the samples removed from the plastic liner and placed in bags on location were exposed to more oxygen. The additional oxygen may have had an effect on the pH, causing the values to be higher in most instances. Figure I8 compares pH measured on location with the data presented in the previous figure. These data show that, in most instances, pH values were higher when measured in the field than values measured for either the encased or bagged soil samples after 4 days of transport. These data further support the need to measure pH on location when at all possible. Resistivity values in Figure I9 were very similar and the type of shipping container did not appear to have a significant effect.

Figures I10 through I15 graphically show the difference in corrosion potentials measured with respect to $Cu/CuSO_4$ and Pt reference electrodes in the corrosion probe at the Buffalo, CCT, and LaGuardia sites. Although a high impedance electrometer was used for both potential measurements, the potentials were observed to slowly drift toward zero when measured with respect to the platinum. At the Buffalo and CCT field sites, comparison of the corrosion potentials measured with respect to $Cu/CuSO_4$ with those measured with respect to Pt showed fairly consistent differences during any one measurement time, but the magnitude of these differences changed over time. However, both electrodes appeared to indicate the same trend in potential over time. At the LaGuardia field site, the potential data showed highly inconsistent potential differences between the two electrodes during each measurement time period although both electrodes appeared to indicate relative trends in potential with depth. Unlike at the Buffalo and CCT field sites, the magnitude of the potentials measured with respect to $Cu/CuSO_4$ and Pt at the LaGuardia site drifted in opposite directions with time. It was believed that the platinum may have had too high an impedance, even for the electrometer, and/or developing films influenced the measured values. Potential measurements, using a Pt electrode, will not be recommended in the future because of these inconsistencies.

Figures I16 and I17 compare corrosion rates calculated from laboratory electrochemical and gravimetric measurements with those same type measurements performed in the field for the Buffalo and CCT sites. No lab soil cell tests were performed with soil sampled from the LaGuardia site. These data show that corrosion rates calculated from field PR measurements more closely approximated corrosion rates calculated from field weight-loss data than did laboratory measurements. At the Buffalo site, where the soil was corrosive, the corrosion rates calculated from field probe weight-loss data were higher, albeit similar to rates predicted from weight-loss data obtained from the laboratory test cells. However, at the CCT site, where the soil was non-corrosive, almost all of the laboratory measurements overestimated corrosion rates as compared with rates measured with the field probe. Corrosion rates calculated from galvanic currents measured with field probes showed macrocell corrosion to have a minor contribution to the total corrosion rate at the Buffalo and CCT sites. Data in Tables F4 and G4, on the other hand, show that macrocell corrosion was more significant to the total corrosion rate with the laboratory probes.

Laboratory soil cells did not appear to adequately predict corrosion rates or simulate field conditions. Some of the differences between the lab and field data may be due to not accounting for solution resistance in the lab PR data. The primary differences were thought to be from changing soil chemistries in the lab soil cells because moisture and oxygen concentrations could not be well maintained in these cells. Thus, soil cell testing is not recommended in further work described in the Strategic Research Plan in Chapter 4.

MODELING

Two types of models were developed in the program. These two types of models were (1) Finite Element Analysis model, and (2) Statistical Prediction model. Each of these models is discussed separately in the paragraphs below.

Finite Element Analysis

The Finite Element Analysis (FEA) model was used to address the two unresolved issues, identified from the literature search, associated with the water table. One issue is the effect of the relative length of the pile above and below the water table on the magnitude of the galvanic effect. In one Army Corps of Engineers report from the 1960s (14), it was suggested that the ratio of the length of piling below the water table to that above the water table affects the maximum severity of attack. For instance, where the length of piling below the water table is large, the maximum corrosion is reduced. This behavior is reasonable for macrocell corrosion in that a large anode/small cathode reduces attack. A better understanding of this effect would help identify those piles that are most prone to severe corrosion.

The second issue, with regard to the water table, is the maximum distance below the water table where galvanic corrosion is likely. Information on this is very limited, but the distance should be a function of soil resistivity, the kinetics of the oxidation and reduction reactions, and the potential difference between the anode and the cathode. It is important to establish this distance in order to limit the portion of each pile requiring examination or assessment.

The FEA model was generated, using a commercially available three dimensional heat flow model, in which potential is analogous to temperature and current is analogous to heat flux. The geometry of the model simulated a 12.2-m (40-ft) wide by 33.5-m (110-ft) deep section of soil. The water table was located 10 ft below the surface, with the remaining 30.5 m (100 ft) below the water table. A polarization curve, which was generated in the lab, from a Buffalo, NY soil sample, was input into the model to characterize the behavior below the water table as well as a convection coefficient boundary condition along the pile/soil interface. A second polarization curve was created by shifting the voltages in the first curve by 300 mV, for instance, $E_{corr} = -750$ mV shifted to $E_{corr} = -450$ mV. This curve was input to characterize the soil above the water table. A convection coefficient was also input as a boundary condition along the pile/soil interface above the water table. Using these conditions, the analysis was aborted by the software, most likely because it was unable to deal with two polarization curves.

A second attempt to simulate the soil conditions was made by inputting the polarization curve associated with the soil below the water table and a voltage of -0.450 V was applied, as a boundary condition, to the pile/soil interface above the water table. Although this analysis was completed, the results were unrealistic and did not correspond with actual behavior in the field.

Several other trials were run, using various loading conditions, to no avail. Therefore, the FEA modeling attempts to simulate field conditions were abandoned.

Prediction Modeling

The purpose of this work was to develop and verify a statistical model to identify soil conditions where unacceptable rates of corrosion of steel piles are likely to occur and to estimate these corrosion rates.

Statistical analysis was performed on corrosion data for a combined data set created from the three sites. Table 3 provides the data used in this analysis. Note that there are only eight observations. The sample number provides linkage to the soil analyses provided in Appendixes F, G, and H in this report. Samples 2 and 3 are from the CCT site, 4 through 6 are from the Buffalo site, and 7 through 9 are from the LaGuardia site. These data were derived by averaging the corrosion rates calculated from weight-loss (W_loss) data across the corresponding raw samples.

TABLE 3 Raw data used in the statistical analysis

W_loss	Sample	Gravel	Sand	Fines	CEC	pH	Res_rec	Res_sat	Chloride	Sulfate	Moisture	G_curr	Polar	Pot_last
0.2778	2	23.15	63.12	13.73	4.88	7.12	6900	2550	24	35	11.8	−0.0074	0.59	−120.8
0.26067	3	11.91	77.53	10.56	5.53	7.3	2220	2220	6	56	30.8	0.01533	0.52	−123.33
7.03	4	35.17	57.99	6.84	3.76	7.95	110	420	5593	260	10.2	0.197	4.97	−677
6.715	5	72.2	22.66	5.14	4.51	8.0	127	120	5065	215	26.9	−0.531	3.445	−677.5
5.6067	6	83.62	14.65	1.73	1.56	8.2	1150	348	2261	724	12.0	0.243	1.92	−693.667
1.24775	7	2.34	93.06	4.6	0.41	7.0	37000	8400	10	32	9.4	−0.15875	0.04	−453
0.9995	8	1.31	97.33	1.36	0.21	7.05	11000	11000	10	28	17.6	0.569	11.68	−745.5
0.9115	9	0.99	96.34	2.67	0.31	7.18	11000	8200	10	32	17.9	0.6465	11.68	−745.5

The variables shown as column headings in Table 3 and in the plots in Appendix J, not published herein, are defined as follows:

W_loss Corrosion rate calculated from weight-loss measurements, mpy
Sample   Sample number from Tables F1, G1, and H1 in Appendices F, G, and H, respectively. Samples 2 and 3 are from the CCT site, 4 through
      6 are from the Buffalo site, and 7 through 9 are from the LaGuardia site.
Gravel   % Gravel
Sand   % Sand
Fines   % Fines
CEC   Cation exchange capacity, meq/100g
pH   pH based on ASTM Method D 4972 measured in calcium chloride water
Res_rec   Resistivity, as-received, ohm-cm
Res_sat   Resistivity, saturated, ohm-cm
Chloride   Soluble Chloride, mg/kg
Sulfate   Soluble Sulfate, mg/kg
Moisture   % Moisture
G_curr   Corrosion rate calculated from galvanic current measurements, mpy (final measurement)
Polar   Corrosion rate calculated from polarization resistance (PR) measurements, mpy (final measurement)
Pot_last   Corrosion potential, mV, with respect to copper/copper sulfate ($Cu/CuSO_4$) reference electrode (final measurement)

Additional predicted variables are

FITS1 – Predicted (or Fitted) values for corrosion rates from weight-loss data from the statistical model
RESI1 – Residuals (Difference between predicted and actual corrosion rates from weight-loss data)

Table 4 is the correlation matrix for the data. The important column to review is the first column titled W_loss. The values below this show the correlation of the various independent variables with the corrosion rate calculated from weight loss (W_loss). Large (close to 1) positive values indicate a strong positive correlation between the given independent variable and the dependent variable weight loss. Large negative values (close to −1) indicate a strong negative correlation between the two variables. A negative correlation implies that increases in the independent variable will cause decreases in the dependent variable weight loss.

Equation 3 is the regression equation fit to these data. Keep in mind that this is based on only eight observations; however, it appears to be a good model for this small data set. Only two independent variables (pH and chloride) are in this model. It is anticipated that future statistical analyses, discussed in the Strategic Research Plan given at the end of Chapter 4, will result in a model that incorporates other variables as well.

The regression equation is

$$W\_loss = -17.2 + 0.000761\ chloride + 2.52\ pH \qquad (3)$$

As shown in Table 5, the R^2 is very high (96.6%) as well is the Adjusted R^2 (95.3%) that adjusts the normal R^2 for the available degrees of freedom. Both pH and chloride are significant at the 95 percent confidence level (as seen by $P \leq 0.05$). Perhaps even more encouraging are the relatively small residuals from the model. The residuals (RESI1) are the difference between the model predicted value (FITS1) and the values shown as corrosion rate calculated from weight loss (W_loss) measurements. These values are given in Table 6. Note that all residuals are < 1.

Plots of the dependent variable shown as corrosion rates calculated from weight-loss (W_loss) measurements as a function of each of the independent variables listed in Table 3 are shown in Appendix J, which is not published here.

It must be cautioned that, because of the limited amount of data, this model should not be used for predictive purposes at this time. Furthermore, there are a number of concerns with the model. The values of the dependent variable (weight

22

TABLE 4 Correlations (Pearson) for the raw data

	W_loss	Gravel	Sand	Fines	CEC	pH	Res_rec	Res_sat	Chloride	Sulfate	Moisture	G_curr	Polar
Gravel	0.802												
Sand	-0.771	-0.991											
Fines	-0.282	-0.129	-0.005										
CEC	0.175	0.307	-0.420	0.818									
pH	0.924	0.920	-0.900	-0.204	0.286								
Res_rec	-0.474	-0.567	0.597	-0.183	-0.588	-0.649							
Res_sat	-0.655	-0.783	0.846	-0.418	-0.763	-0.797	0.683						
Chloride	0.957	0.683	-0.676	-0.094	0.346	0.836	-0.519	-0.677					
Sulfate	0.685	0.852	-0.812	-0.348	-0.019	0.851	-0.429	-0.587	0.475				
Moisture	-0.102	0.036	-0.056	0.143	0.460	0.031	-0.408	-0.158	-0.003	-0.221			
G_curr	-0.330	-0.435	0.494	-0.409	-0.586	-0.279	-0.023	0.540	-0.402	-0.036	-0.256		
Polar	-0.088	-0.340	0.423	-0.591	-0.568	-0.192	-0.087	0.585	-0.082	-0.227	0.035	0.741	
Pot_last	-0.542	-0.255	0.136	0.892	0.635	-0.397	0.068	-0.208	-0.427	-0.360	0.197	-0.364	-0.682

loss) and of one of the independent variables (soluble chloride) cluster in two extreme groups. Samples 4, 5, and 6 have high values and all others have relatively low values. The higher correlation and large proportions of explained variance may be due primarily to this bimodal tendency in the distributions. The pH coefficient also is contrary to the researchers' fundamental understanding of corrosion processes. The corrosion rate of carbon steel should decrease with increasing pH yet, the negative coefficient is indicative

of the opposite behavior. Again, this behavior can be attributed to the bimodal nature of the data set.

Rather, this model is indicative of the type of procedure that could be used in future modeling efforts along with any other methodologies appropriate for the available data. Regression diagnostics including statistical tests of model parameter significance and goodness of fit procedures would be included in the Minitab generated computer output as given in Table 5. Minitab, SAS, and SPSS are several of the possible statistical packages that could be used in future modeling efforts discussed in the Strategic Research Plan.

TABLE 5 Statistical parameters and analysis of variance for the model

Predictor	Coef	StDev	T	P
Constant	-17.182	6.625	-2.59	0.049
Chloride	0.0007608	0.0001859	4.09	0.009
pH	2.5188	0.9192	2.74	0.041

S = 0.6526 R^2 = 96.6% R^2(adj) = 95.3%

Analysis of Variance

Source	DF	SS	MS	F	P
Regression	2	60.943	30.472	71.56	0.000
Error	5	2.129	0.426		
Total	7	63.072			

TABLE 6 Residuals from the model

W_loss	FITS1	RESI1
0.27780	0.770818	-0.49302
0.26067	1.210515	-0.94985
7.03000	7.098575	-0.06858
6.71500	6.822795	-0.10779
5.60670	5.193169	0.413531
1.24775	0.457905	0.789845
0.99950	0.583847	0.415653
0.91150	0.911296	0.000204

23

LONG-TERM RESEARCH

Analysis of the laboratory and field testing performed in this project suggest the need for longer-term testing, which is outside the scope of the present program. For instance, the field corrosion probe needs to be re-designed to make it easier to assemble and disassemble and needs to be more rugged to withstand the forces encountered in probe placement. Furthermore, three field sites yielded a very small data set for predictive modeling efforts. Data needs to be acquired from more field sites, and field corrosion probes need to be installed over much longer periods than 120 days. Additionally, the effects of stray current corrosion on the corrosivity of piling could not be addressed within the scope of the current project. The results of these additional studies would be used to update the Recommended Practice.

Recommendations for future research are contained in the Strategic Research Plan given at the end of Chapter 4. The purpose of the Strategic Research Plan is to identify the research necessary to achieve the long-range objectives on corrosion of steel piling. These objectives are

- Develop a means to determine the condition and to estimate the useful life of steel piling, and
- Assist bridge engineers and owners in their decision-making with regard to the use of existing and new steel pile supports for structures.

The primary focus of the Strategic Research Plan is on those activities requiring long-term research that are outside the scope of the current research program.

The activities in the Strategic Research Plan all feed into a statistical model. The goals of developing this model are to identify soil conditions where unacceptable rates of corrosion of steel piles are likely to occur and to estimate these rates of corrosion. The Strategic Research Plan emphasizes field corrosion rate measurements and the tasks are designed to provide the data required to develop and confirm the model.

The following tasks have been identified for the Strategic Research Plan:

Task 1—Instrumentation Development,
Task 2—Field Studies,
Task 3—Pile Database,
Task 4—Laboratory Support,
Task 5—Statistical Modeling,
Task 6—Marine Applications,
Task 7—Stray Current Corrosion,
Task 8—Recommended Practice Update, and
Task 9—Analysis and Reporting.

Further details of each task, along with a schedule and budget, are given at the end of Chapter 4 under the heading "Suggested Research."

REVISED RECOMMENDED PRACTICE

Modifications to the Recommended Practice

Modifications to the Draft Recommended Practice were substantial. Procedures and analysis techniques that were found to be redundant or unnecessary to fully characterize the corrosivity of a site or the conditions of piling were eliminated. There also was significant input from the NCHRP Project Panel on modifications to the Practice to make it concise, understandable to a bridge engineer or state geotechnical engineer, and easy to use.

The Final Recommended Practice is given in Appendix K, which is not published here. Justifications for the procedures selected in the Recommended Practice are given in Appendix L. Further discussion of the justification is given in the section titled "Comparative Analyses." Some of the significant changes to the Practice include the elimination of

1. All water analyses,
2. CEC analyses, and
3. Eh measurements.

Results of the soil and water analyses described previously demonstrated that the levels of aggressive ions in the soil below the water table were comparable to the levels of these ions in the ground water. Similar trends in resistivity also were observed for the soil and water samples. Typical data are shown in Figure 3. Therefore, the water analyses did not provide information that was not available from the soil analyses.

Chloride and sulfate analyses were retained in the Recommended Practice but were removed from the decision trees. Results of the chloride and sulfate analyses from the Buffalo and CCT sites were compared with the measured saturated soil resistivities at those sites. When the concentrations of the two anions were summed, the data fell on the theoretical trend for the effect of these anions on resistivity in water, see Figure 4. This behavior indicates that the primary contributors to conductivity in these soils were those ions. With this knowledge, and the established correlation in the literature between soil resistivity and corrosivity, it became clear that the effects of these anions on corrosivity could be characterized by resistivity measurements for these soils. On the other hand, results of sulfate and chloride analyses may be useful in evaluating unusual conditions.

The decision to eliminate the microbial analyses was based on the fact that microbes are found in most all natural water, and it is difficult to establish a cause and effect relationship between their presence and the occurrence of significant corrosion. The literature and the data generated in this research did not provide any guidance with respect to minimum levels or types of microbes that would contribute to significant corrosion. With respect to CEC, previous

Figure 3. Comparison of chloride and sulfate contents of soil and water sampled at the Buffalo and CCT field sites.

research has shown a correlation between CEC and corrosivity, but it was believed that there was insufficient information currently available to warrant inclusion of CEC in the Recommended Practice. Either or both CEC and microbial analyses may be included in the Recommended Practice at a later date, depending on the results of additional field testing. Eh measurements were removed from the Recommended

Practice because of observed inconsistencies found in the Eh measurements from the field probes.

As described in the section titled "Comparative Analyses," an evaluation was performed on three techniques for measuring soil pH, ASTM Method G 51 and two techniques in ASTM Method D 4972. It was found that ASTM Method G 51 generally gave the lowest values, which were 0.5 to

Figure 4. Resistivity as a function of anion concentration of soils sampled at various field sites compared with theoretical data plotted for $CaSO_4$ and $NaCl$ solutions at ambient temperature.

1 pH unit lower than the other two techniques. Typical data are shown in Figure 5. Therefore, ASTM Method G 51 provides a worst-case indication of the soil pH. In this evaluation, it also was found that ASTM Method G 51 could not be used for soils with very large particle sizes. Accordingly, the ASTM Method G 51 was specified for the Recommended Practice except where such soils are encountered. For gravel-sized soils, ASTM Method D 4972 is recommended and the pH value measured with this technique should be reduced by 0.5 to 1 pH units for comparison with pH measured by ASTM Method G 51.

An evaluation also was performed on sampling and handling methods for the soils. Based on this evaluation, it was concluded that a 3-in. split spoon is the best method for soil sampling because a continuous, minimally disturbed sample is obtained and the quantity of soil is sufficient for the specified analyses. It also was found that the pH and resistivity of the soil sample were a function of the storage method and the storage time between sampling and analysis. Accordingly, it is recommended in the Practice that soil samples be stored in well-sealed glass jars that retain moisture and exclude oxygen. It is further recommended that the laboratory analyses be performed within 1 to 2 days of sampling.

Other changes to the Recommended Practice include more emphasis on uniform corrosion than was found in the draft and the inclusion of a brief discussion of stray current corrosion. Results of the literature search indicated that uniform corrosion is not a significant contributor to underground corrosion of structural steel. On the other hand, the results of the

field and laboratory data indicate that uniform corrosion can be a significant contributor, at least over short exposure times. The longer exposure times outlined in the Strategic Research Plan will help to resolve this issue. Thus, an assessment of uniform corrosion is included in the Recommended Practice.

Evaluation of Revised Recommended Practice

The predictive capability of the Revised Recommended Practice was evaluated by applying the decision trees in Figures K-3 and K-4 of the Recommend Practice, given in Appendix K (not published here), to about a dozen pile sites. The corrosive sites were taken from Table D-1 in Appendix D and the non-corrosive sites were taken from NBS Monograph 127 (*10*). A summary of information on these sites and the predictions of the Recommended Practice are given in Table 7. The portions of the piles well below the water table were treated as piles that were located below the water table for the analysis. As indicated in the Recommended Practice, a pile located below the water table would be expected to experience low corrosion rates regardless of the soil resistivity, pH, or other properties. For the analysis, isolated pitting, which was commonly observed above the water table, was not considered to affect the life of a pile.

The first six cases in the table were all considered to have experienced significant corrosion attack in the field examinations. Significant corrosion was defined as a uniform loss

Figure 5. Comparative pH data, using three test methods for soil sampled at the CCT site as a function of depth.

TABLE 7 Evaluation of Recommended Practice for corrosive and non-corrosive pile sites

Location	Age Year	Location with Respect to Water Table	Soil Type	pH	Resistivity ohm-cm	Thickness Loss, %	Corrosion Rate MPY*	Recommended Practice		Correct Prediction
								Uniform Corr. Rate	Galvanic Corr. Rate	
Buffalo, NY (11)	32	At or Near	silt/slag/cinder	9.0	733	32	2.2	Low	High	Yes
Hartford, CT (12)	29	Above	clay/coal/ash	3.8	380	65	4.2	High	High	Yes
Sparrows Point, MD (13)	18	At or Near	slag/sand/cinder	3.7	1130	29	4.4	High	High	Yes
Boardman, NC (13)	37	At or Below	fine sandy loam	3.4	1240	40	1.4	High	High	Yes
Sardis Dam, MS (13)	–	5' Below	riprap/gravel	3.0	610	19	1.7	High	High	Yes
Grenada Dam, MS (13)	–	Above	silty sand	6.4	4000	19	3.1	Low	Low	No
Stoplog Dam, TX (10)	21	Above	silty clay	7.5	150	P** (50 mils)	2.4 (P)***	Low	High	No
Stoplog Dam, TX (10)	21	Below	clay/silty clay	7.2	100	0	0	Low	Low	Yes
Minnesota City, MN (10)	29	Above	sand	7.2	36000	P (10 mils)	0.3 P	Low	Low	Yes
Minnesota City, MN (10)	29	Below	silty sand	4.7	1860	0	0	Low	Low	Yes
Dresback, MN (10)	27	Above	sand	7.5	44000	P (55 mils)	2.0 P	Low	Low	Yes
Dresback, MN (10)	27	Below	sand/silt	6.8	3100	P (10)	0.3 P	Low	Low	Yes
Winona, MN (10)	28	Above	sand	7.5	41000	P (55 mils)	2.0 P	Low	Low	Yes****
Winona, MN (10)	28	Below	silty sand	6.8	2660	0	0	Low	Low	Yes
Buffalo, NY (10)	36	Above	clay/silty sand	7.8	1610	P (50 mils)	1.4 P	Low	High	No
Erie, PA (10)	32	Above	sand	7.9	23000	P (65)	2.0 P	Low	Low	Yes
Fairport, OH (10)	30	Above	clay/sand/gravel	8.0	4200	–	<0.7	Low	Low	Yes
Fairport, OH (10)	30	Below	clay/sand/gravel	7.2	1120	0	0	Low	Low	Yes

*   One-Sided Corrosion Rate, mpy   *** Maximum Rate of Isolated Pitting

** Isolated Pitting   **** Isolated pitting is not considered to seriously affect piling life

of section of greater than 15 percent of the thickness of the piling at any single location. This section loss corresponds to a loss of about 1/3 (33%) of the useful life of the pile based on a failure criterion of 50 percent thickness loss. Isolated pitting is excluded from the criterion, as described above. The corresponding corrosion rate for this thickness loss is a function of the thickness and type of the pile and the time the pile has been in the ground. A reasonable magnitude of a significant corrosion rate, based on the first six cases, is 1 mpy. This value would correspond to a one-sided corrosion rate and the rate of loss in section of an H-pile would be twice this value.

The far right column in Table 7 indicates that the decision tree in the Recommended Practice correctly predicted the severity of corrosion in 15 out of 18 (83%) cases. This is excellent performance for such a simple model. One likely source of error in the prediction is associated with the degree of compaction of the soil. The NBS work found that piles driven through undisturbed soil did not experience significant corrosion regardless of the soil properties. The Stoplog Dam soil and the second Buffalo soil were predicted to be corrosive (above the water table) based on resistivity but only isolated pitting was observed. These sites may have been highly compacted, excluding access of oxygen to the pile.

CHAPTER **3**

INTERPRETATION, APPRAISAL, AND APPLICATION

Several important issues were identified in NCHRP Project 10-46 that affect the application of the findings of the work to the overall program goal of determining the condition and estimating the useful life of steel piling. These are in the areas of the mechanism of underground corrosion, testing procedures that should be included in the Recommended Practice, and the role of modeling. Further discussions of these issues is given below.

CORROSION MECHANISM

One conclusion of the state-of-the-art survey is that the primary mechanism for severe corrosion of steel in soils is an oxygen macrocell. The mechanism is associated with a variation in the concentration of oxygen in the soil over the surface of the underground structure. Areas that are deficient in oxygen become anodes in the corrosion cell and experience accelerated attack. Areas that are oxygen rich become cathodes and the rate of corrosion in these areas is reduced. These conditions normally occur in stratified soils above the water table.

Techniques for measurement of the relative contribution of uniform corrosion and macrocell corrosion to attack of steel were included in the corrosion testing performed in the laboratory and the field. These techniques included polarization resistance, weight loss, and galvanic current measurements and the corrosion rates calculated from each of these techniques were compared. Significant macrocells would not be expected to develop on small specimens unless they were electrically coupled to specimens exposed in different strata of soils. Results of the testing indicated that uniform corrosion was a major contributor to the corrosion process, especially in the most corrosive Buffalo soil. This unexpected finding, if confirmed with longer-term testing, suggests that field corrosion monitoring should include techniques for the measurement of uniform corrosion rates. The field corrosion probe was designed for this project with the idea that the primary concern is macrocell corrosion. This design will require modification to facilitate the monitoring of rates of uniform corrosion. It is also possible that longer-term exposures are required for the macrocells to develop and become dominant. In the soils having lower corrosivity, there was evidence that rates of uniform corrosion decreased with time such that the contribution of macrocell corrosion to the total corrosion

increased with time. On the other hand, rates of uniform corrosion did not appear to decrease with time for the corrosive soils such that this process may not operate in situations where corrosion rate predictions are most critical.

TESTING PROCEDURES

A number of testing procedures for the evaluation of the corrosivity of soils and waters was included in the Draft Recommended Practice. Procedures also were included in the Draft Recommended Practice for field corrosion monitoring. Similar procedures were used in the laboratory for evaluating the corrosivity of the soils obtained from the field sites.

Difficulties were encountered in controlling the test conditions for the laboratory corrosion tests. The major problem was in controlling the moisture content of the soils over long periods. In tests with different soil strata, it is unlikely that adequate control could ever be maintained. It also was speculated that a poor correlation between laboratory and field corrosion data may have been the result of difficulties encountered in controlling the oxygen concentration in the soil. It is very difficult to simulate field conditions in the laboratory when one considers the dynamic relationship between moisture content and oxygen in a soil environment. As the water table lowers in dry periods, oxygen laden air is pulled into the soil while most of the oxygen is excluded as the water table rises. Considering these issues and the need for long-term corrosion testing, it was recommended that future research focus on field corrosion rate measurements. The laboratory support should be restricted to soil analyses unless specific issues that can be readily assessed in the laboratory are encountered.

Results of the testing identified several ways to simplify the final version of the Recommended Practice. For example, it was found that the water analyses could be eliminated from the Practice since the results of those analyses were similar to results of soil analyses taken from the same soil strata. The CEC analyses did not provide any measurable improvement in the prediction capabilities of the Practice, based on a simple engineering assessment of the field data, and were eliminated. These or other techniques may be reintroduced in the Practice by AASHTO as further field information becomes available.

The final version of the Recommended Practice is a very streamlined, concise document that uses four soil parameters to assess the corrosivity of a field site. These parameters are soil resistivity, soil pH, soil particle size, and position of the pile with respect to the water table. When this Practice was applied to 18 field cases, including 6 corrosive sites and 12 non-corrosive sites, it gave an accurate prediction of the corrosivity of the sites in over 80 percent of the cases. Considering the preliminary nature of the Recommended Practice, this is considered to be excellent predictive capability. It is unlikely that any model or practice can greatly improve on this predictive capability because of inherent inaccuracies in the field data and the many unique conditions that can be encountered.

MODELING

The purpose of the statistical modeling activity on the project was to establish a framework for an analytical model for predicting the corrosion of steel piling in soil environ-ments. A regression model was developed from the results of the analyses of the soils at the field sites and the corrosion monitoring data from these sites. This model gave a good fit to the data using only two variables—pH and chloride. The adjusted R^2 value of the model was 95 percent. In a sense, this model is consistent with the decision tree developed in the Recommended Practice in that both use a very small number of variables and these variables are similar. On the other hand, the model demonstrates the inadequacies of a regression model developed on a limited data set. The coefficient for the pH term in the model is positive, which indi-cates that the corrosion rate increases with increasing pH. This conclusion is contrary to our fundamental understand-ing of corrosion mechanisms. The positive pH coefficient occurred because the one corrosive site had higher pHs than the two non-corrosive sites. It is interesting to note that the corrosion monitoring data did not contribute to the predictive capability of the model, indicating that the data were not use-ful in predicting corrosion rates. This conclusion may reflect the short-term nature of the corrosion rate data.

CHAPTER **4**

CONCLUSIONS AND SUGGESTED RESEARCH

CONCLUSIONS

The potential magnitude of the problem of corrosion of steel piling in soil is quite large. Conditions that are conducive to severe corrosion of steel piles are commonly found in pile foundations for bridges. These include the presence of fill soils containing manufactured materials, such as slag, ash, or cinders or soil containing contamination from salt-water runoff or other sources.

Results of the state-of-the-art survey indicate that the controlling mechanism for severe corrosion of steel in soils is thought to be well understood. The presence of moisture and oxygen are required for the corrosion to occur. The specific mechanism is referred to as an oxygen macrocell and is associated with a variation in the concentration of oxygen in the soil from one area to another on the underground structure. These conditions normally occur in stratified soils above the water table. Other factors that have been associated with soil corrosivity include soil resistivity, pH, soil particle size, and the concentration of deleterious anions such as chlorides and sulfates. While the mechanism of underground corrosion and many of the controlling factors are thought to have been identified, prior attempts to predict soil corrosivity have met with limited success. Typically, there is a lot of scatter in the data and correlation coefficients are low.

Results of laboratory and field testing indicate that the mechanism of uniform corrosion in the corrosive soil strata may be a major contributor to pile failure, but the tests may have been of too short a duration for macrocells to properly develop. Macrocells may dominate corrosion behavior in longer-term tests and on actual piles. This finding was unanticipated and, if confirmed by longer-term testing, would complicate the procedures used for monitoring the corrosion rates of piles.

The results also indicate that a relatively small number of variables are required to describe the corrosivity of a field site. These variables may include soil resistivity, soil pH, soil particle size, and the position of the pile with respect to the water table. A simple decision tree that is based on this information was incorporated into a modified version of the Recommended Practice. When the procedures outlined in the modified Recommended Practice were tested out on case histories found in the literature, it was found that the decision tree could correctly identify the potential corrosivity of a field site in more than 80 percent of the cases.

SUGGESTED RESEARCH

Strategic Research Plan

Recommendations for future research are contained in the Strategic Research Plan. The purpose of the plan is to identify the research necessary to achieve the long-range objective on corrosion of steel piling. This objective is to develop a means to determine the condition and to estimate the useful life of steel piling. This information will assist bridge engineers and owners in their decisionmaking with regard to the use of existing and new steel pile supports for structures.

The primary focus of the Strategic Research Plan is on those activities requiring long-term research that are outside the scope of the current research program.

As described below, the activities in the Strategic Research Plan all feed into a statistical model. The goals of developing this model are to identify soil conditions where unacceptable rates of corrosion of steel piles are likely to occur and to estimate these rates of corrosion. The Strategic Research Plan emphasizes field corrosion rate measurements, and the tasks are designed to provide the data required to develop and confirm the model.

The following tasks have been identified for the Strategic Research Plan:

Task 1—Instrumentation Development,
Task 2—Field Studies,
Task 3—Pile Database,
Task 4—Laboratory Support,
Task 5—Statistical Modeling,
Task 6—Marine Applications,
Task 7—Stray Current Corrosion,
Task 8—Recommended Practice Update, and
Task 9—Analysis and Reporting.

Further details of each task are given below.

Research Plan Tasks

Task 1—Instrumentation Development. The purpose of this task is to optimize the instrumentation that will be used for field corrosion monitoring in Task 2. The corrosion probe developed in NCHRP Project 10-46 was found to be effective at detecting macrocells in the soil strata and in estimating the corrosion rate as a function of depth. Some deficiencies with the current probe design were identified. For example, difficulties were encountered in forming watertight seals between the individual electrodes in the probe. In a few cases, the probe also was found to be damaged during installation. In this task, the design of the probe will be modified to make it more rugged and easier to assemble and disassemble.

Other proposed modifications to the probe are due to the results of analysis of field corrosion data. The Eh measurement capability of the existing probe was found to be of limited value because potentials measured with respect to a Pt electrode were quite variable. It was speculated that this variability occurred as a result of deposition of corrosion products on the Pt electrode used for the measurements. Accordingly, the Eh measurement capability will be eliminated from the new probe design. On the other hand, results of the short-term field measurements with the existing probe indicated that uniform corrosion may contribute significantly to the rate of corrosion of a pile in corrosive strata. Accordingly, the new probe will be designed to more readily measure uniform corrosion rates using the polarization resistance technique. The capability of the probe to measure the resistivity of adjacent soil layers also will be evaluated in this task.

New technologies for monitoring corrosion rates will be investigated in this task. Specifically, the applicability of techniques used to monitor casings in oil and gas wells will be assessed. Several types of inspection devices are used in the oil and gas industry for the inspection of well casings. These include magnetic flux leakage and ultrasonic tools for measuring wall loss and a casing potential profile tool for measuring stray current corrosion and cathodic protection currents. The concept is to install a pipe pile (having a diameter similar to that used for well casings) near piling in potentially corrosive soils and monitor the pipe pile to assess the corrosion behavior of the piling.

In this task of the program, monitoring piles will be installed in corrosive soil at a few sites along with corrosion probes, and the behavior of the pile will be compared with that of the probe. The performance of the monitoring techniques will be confirmed by removal and assessment of the probe and monitoring pile. The corrosion rate of the pile and the probe will be accelerated by anodic polarization with a rectifier and a remote ground bed to reduce the test time required to obtain measurable corrosion.

Task 2—Field Studies. The purpose of this task is to collect long-term corrosion rate and soil data from a number of field sites. These data will be used to confirm and optimize the corrosion monitoring techniques and to develop and confirm the corrosion prediction model.

Results of NCHRP Project 10-46 indicated that uniform corrosion may make a significant contribution to the overall degradation of a pile. On the other hand, prior research has indicated that macrocell corrosion is the dominant mechanism of corrosion of underground structures. This discrepancy may be the result of the short-term nature of the results of NCHRP Project 10-46. Accordingly, much longer-term data are needed to resolve this issue.

The NCHRP Project 10-46 work also identified several soil parameters that correlate with soil corrosivity. These parameters will form the basis of a statistical model to predict soil corrosivity. The data collected in this task will be used to refine the initial model and to place that model on a sound statistical basis.

Field sites will be selected to cover a broad range of soil conditions from around the country. For costing purposes, a total of 12 nonmarine field sites are proposed. These sites may or may not have existing piles. It will be imperative for the sites to have long-term access for these field studies. It may be possible to obtain access to the Geotechnical Experimental Sites around the country for use as field sites on this program.

At each field site, soil samples will be obtained from the significant strata down to the water table as described in the Recommended Practice. Three probes and a small-diameter pipe pile will be installed at each field site. The probes will be monitored two times per year and a probe will be removed and evaluated after 2, 5, and 10 years. Based on the measured corrosion rate, a time for the first inspection of the pipe pile will be established. For example, if a corrosion rate of 5 mils per year is measured and the magnetic flux leakage technique has a threshold of 5 percent of the wall thickness, then a time for first inspection of 5 years would be reasonable for a pipe pile having a 0.25-in. wall thickness.

Task 3—Pile Database. The purpose of this task is to develop a database on the existing condition of piles removed or exposed by state DOTs. Whenever piles are being exposed or removed, the condition of the piles will be assessed and soil samples at the pile locations will be obtained and analyzed. For costing purposes, it is proposed that six piles be examined each year of the program, beginning in the fourth year. The pile condition will be correlated with soil properties to better understand the controlling factors in pile corrosion and to improve the corrosion prediction model.

The success of this task will depend on the participation of the state DOTs. Therefore, selling the idea to the states will be required. For each state, the appropriate person will be identified and periodically contacted in order to ensure that most of the exposed piles in the DOT inventory around the country are included in the database.

32

Task 4—Laboratory Support. The purpose of this task is to provide technical support to Tasks 2 and 3. The soil samples obtained from the field sites in Task 2 and the pile locations in Task 3 will be analyzed using the methods identified in the Recommended Practice as well as other methods used in NCHRP Project 10-46. The idea is not to exclude methods that may be found to be useful, based on the long-term field corrosion rate data. The existing methods will be fine-tuned in the task and new methods will be identified and evaluated. The output of this task will be the results of the soil analyses for the field sites and pile locations.

In this work, the majority of the corrosion testing will be performed in the field and little, if any, corrosion testing using soil cells in the laboratory is planned. Long exposure periods are required to establish steady state corrosion rates in soil, and it is difficult to simulate the appropriate moisture and aeration conditions in the laboratory and maintain those conditions over long exposure times.

Task 5—Statistical Modeling. The purpose of this task is to develop and verify a statistical model to identify soil conditions where unacceptable rates of corrosion of steel piles are likely to occur and to estimate these corrosion rates. The basic understanding of the factors controlling underground corrosion is not sufficiently well developed to consider a first principles based model (a model based on scientific laws that are fundamental in nature) for this program. Therefore, a variety of statistical methods will be used in the modeling effort. The methods employed will account for the quality of the available data. For example, regression-based methods such as general linear models that allow qualitative and quantitative independent variables would be the first choice if data quality permits. Such techniques would incorporate qualitative factors (e.g., soil type) as well as quantitative factors (e.g., pH) to predict a continuous, quantitative output of maximum corrosion rate.

If the data quality for the dependent variable (maximum corrosion rate) is not precise, a better model may be developed using log-linear models in which the corrosion rate is categorized into groups such as low, medium, and high corrosion rates. These modeling approaches will allow both categorical (nominal or ordinal) and continuous independent quantitative covariates into the modeling structure.

As described in this report, Task 5 of NCHRP Project 10-46 has identified several parameters that correlate with the corrosivity of the field sites. These parameters will form the basis for the model developed in the follow-on work. However, the current database is limited and the corrosion rate data were obtained from such short exposure times that there is not a lot of confidence in the current results.

A desired deliverable of this task is a sound statistical model with a continuous predictor of maximum corrosion rate, but other approaches may be used depending on the data quality and availability. As indicated above, the statistical model may not be able to accurately predict a continuous

maximum corrosion rate. If this is the case, then a statistical model will be developed that will categorize maximum corrosion rate into ordered categories such as low, medium, and high.

Task 6—Marine Applications. The purpose of this task is to evaluate the applicability of the methodologies developed on this program (for the determination of the condition and the estimation of the useful life of steel piling) to marine locations. In this task, the field studies and pile database will be expanded to include marine sites. The scope will be limited to piling located in marine soils. For costing purposes, a total of three marine sites is proposed. In the field studies, probes and pipe piles will be installed at marine locations and monitored as described in Task 2. Soil samples will be obtained and analyzed as described in Task 4. Exposed piles in marine locations will be included in the database described in Task 3. The predictive capability of the model developed in Task 5 will be evaluated for the marine sites. A separate model will be developed for the marine sites if it is found that the model for nonmarine applications is inadequate.

Task 7—Stray Current Corrosion. The purposes of this task are to establish the minimum potential gradients necessary to cause stray current corrosion of piling and to prepare a section for the Recommended Practice on procedures for assessing the potential for stray current corrosion of steel piling. It is well established that stray current corrosion can cause damage to underground structures but the minimum potential gradient necessary to promote significant damage to piling has not been established. This information is necessary to assist bridge engineers and owners in their decision-making with regard to the need for corrosion mitigation on their support structures.

The approach in this task is to develop a finite element model to evaluate the influence of soil parameters, polarization behavior (at the corroding metal surface) and piling dimensions on the potential for stray current corrosion damage. The model will be similar to that used in NCHRP Project 10-46 to assess the maximum length of a piling that can be affected by macrocell corrosion at the water table.

The finite element model will be verified by performing field tests on instrumented piles placed in a stray current gradient. A stray current potential gradient will be established using a cathodic protection rectifier, an anode ground bed, and a buried joint of line pipe. Piles will be placed between the anode and the pipe, and the piles will be electrically coupled through ZRAs. Each pile will contain several electrodes located at different depths. These electrodes will be coupled together through ZRAs such that the current pick-up and discharge can be measured as a function of depth. The magnitude of the stray current potential gradient will be varied and the effect of that variation on the current pick-up and discharge will be measured. A maximum acceptable stray current potential gradient will be established as a function of

piling dimensions, the cross-sectional area of the pile, the desired life of the pile, and soil parameters.

Task 8—Recommended Practice Update. On a biannual basis, recommendations will be made to update the Recommended Practice developed in NCHRP Project 10-46 as new and better information becomes available. Anticipated changes to the Recommended Practice include the addition of the model to assist in the prediction of useful remaining life of a pile, modifications of the field test procedures to reflect new findings on useful soil parameters and field corrosion monitoring techniques, and the inclusion of rules on stray current assessment. The scope of the Recommended Practice will also be expanded to include marine applications if this change is found to be appropriate, based on the results of Task 6.

Task 9—Analysis and Reporting. In this task, the information developed in the other tasks of the plan will be ana-

lyzed and the reports required by NCHRP will be prepared. These include the monthly, quarterly, phase completion (as described below), and final reports.

Program Schedule and Budget

The schedule for the Strategic Research Plan is shown in Figure 6. The proposed duration of the plan is 12 years. Task 1 has a duration of 30 months and begins at the inception of the plan. Task 2 and Task 4 run for the entire 12-year period. Task 3 starts in the fourth year and runs through to the end of the program. The start of this task was delayed to reduce the annual budget of the program in the first years when the field sites are being set up. Task 5 starts at the beginning of the thirty-first month (as field corrosion probes begin to be removed and analyzed) and runs through to the end of the program. Task 6 begins on the thirty-first month of the plan and runs through to the end of the program. Task 7 begins on the thirty-first month and runs through year 5. Task 8
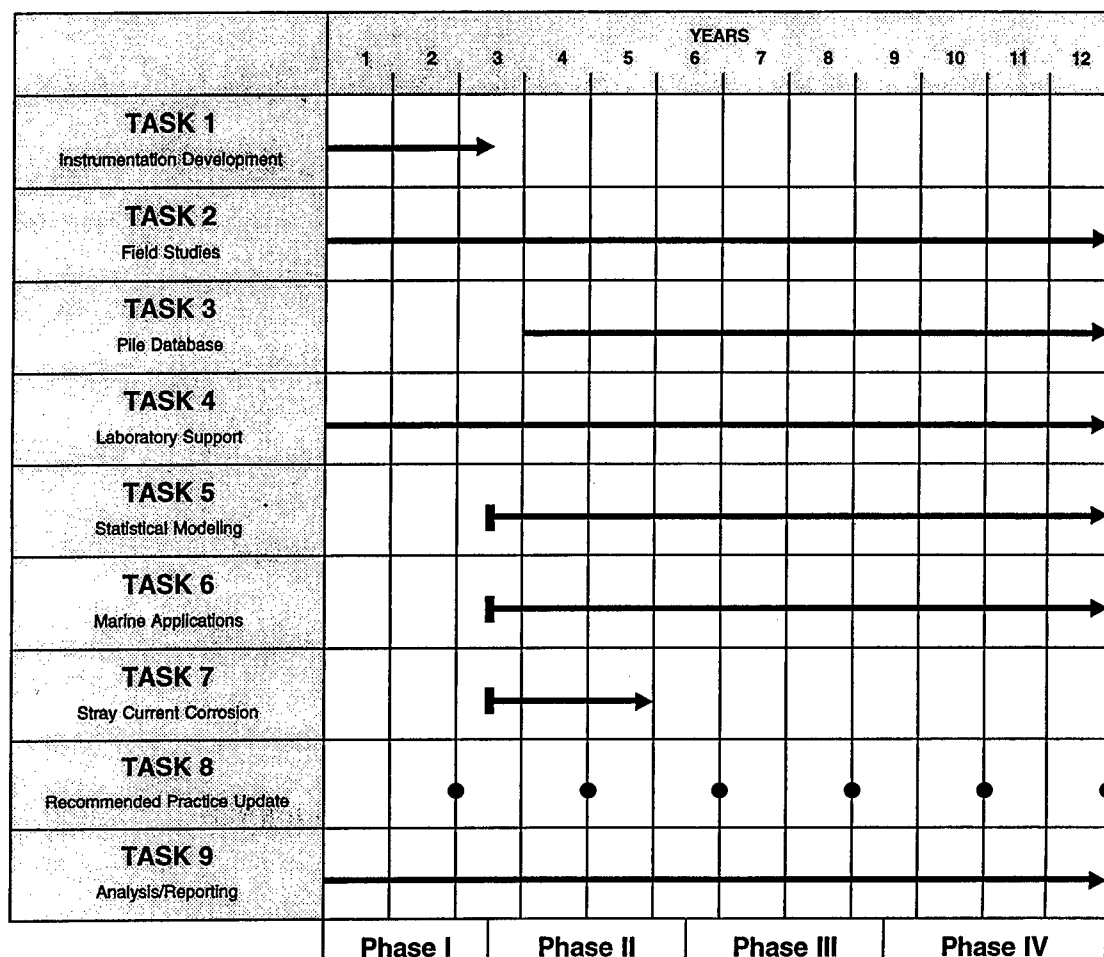

Figure 6.   Strategic Research Plan program schedule.

TABLE 8 Strategic Research Plan program budget

TASKS	Year 1	Year 2	Year 3	Year 4	Year 5	Year 6	Year 7	Year 8	Year 9	Year 10	Year 11	Year 12
Task 1 – Instrumentation Develop.	20	20	10									
Task 2 – Field Studies	110	121	108	60	60	60	60	60	60	60	100	70
Task 3 – Pile Database				15	15	15	15	15	15	15	15	8
Task 4 – Laboratory Support	13	13	5	15	15	15	15	15	15	15	15	8
Task 5 – Statistical Modeling			6.5	13	13	13	13	13	13	13	13	13
Task 6 – Marine Applications			20	50	15	15	15	15	15	15	15	8
Task 7 – Stray Current Corrosion			10	25	25							
Task 8 – Recom. Practice Update		8		8		8		8		8		8
Task 9 – Analysis/Reporting	40	40	40	40	40	40	40	40	40	40	40	80
TOTAL	183	202	200	226	183	166	158	166	158	166	198	195

All budget numbers are in thousands of 1997 U.S. dollars, not corrected for inflation.

involves periodic input on a biannual basis. Task 9 runs the duration of the program.

For costing purposes, the Strategic Research Plan is divided into four phases. Phase I runs from program inception and has a duration of 30 months. This is a very labor-intensive phase in which instrumentation development is completed (Task 1), all of the nonmarine sites are installed (Task 2), and the soils from the field sites are analyzed (Task 4). Phase II runs for a period of 3 years, beginning on the thirty-first month. In this phase, the field sites will be monitored and the first corrosion probes will be removed (Task 2). The pile database will be started (Task 3) and soils from the pile sites will be analyzed (Task 4). The modeling effort will begin (Task 5) and the marine corrosion sites will be installed and monitoring will begin (Task 6). The stray current corrosion task will be performed (Task 7) and updating the Recommended Practice will be continued.

In Phase III of the program, the monitoring activities of the field sites in Tasks 2 and 6 will be continued. The pile database task (Task 3) also will be continued, as will the model-

ing, laboratory support, and Recommended Practice updating tasks. In the final phase of the program (Phase IV), the field sites will be terminated. The nondestructive examination of the installed pipe piles at those sites will be performed and the piles will be removed and examined. The modeling activities will be completed and the final report will be issued.

The budget breakdown by task and year is shown in Table 8. The budget numbers represent thousands of 1997 U.S. dollars and are not corrected for inflation. As shown, Phase I of the program is very labor intensive with the installations of the field sites and the database development. Phase I has a duration of 30 months and a total cost of $485,000. The rate of spending on Phase II also is high because of the start up of the Tasks 3, 6, and 8. Phase II has a duration of 36 months and a total cost of $592,000. In Phase III, most of the tasks are continued, with the exception of Tasks 1 and 7. The duration of Phase III is 36 months and the total cost is $486,000. Phase IV is the completion phase of the program and has a duration of 42 months. The estimated total cost of this phase is $638,000.

REFERENCES

1. Romanoff, M., "Underground Corrosion," *National Bureau of Standards Circular 579*, 1957, reprinted by National Association of Corrosion Engineers, 1989.
2. Lee, R. U. and A. H. Clark, "Corrosion of Steel Pilings in Soil," Corrosion '93, Paper No. 6., National Association of Corrosion Engineers, 1993.
3. Anon., *Annual Book of ASTM Standards*, American Society for Testing and Materials, Philadelphia, Pennsylvania, Vol. 04.08, 1992.
4. Anon., *Standard Specifications for Transportation Materials and Methods of Sampling and Testing*, American Association of State Highway and Transportation Officials, 17th Edition, Washington, D.C., 1995.
5. Anon., *Annual Book of ASTM Standards*, American Society for Testing and Materials, Philadelphia, Pennsylvania, Vol. 03.02, 1992.
6. Long, R. P., J. Badinter, and P. R. Kambala, "Investigation of Steel Pile Foundation in Corrosively Active Areas," Connecticut Department of Transportation, *Report No. JHR 95-239*, Connecticut Department of Transportation, March 1995.
7. Fontana, M. G. and N. D. Greene, *Corrosion Engineering*, McGraw-Hill, New York, New York, 1978.
8. Anon., *NACE Corrosion Engineer's Reference Book*, Ed: R. S. Treseder, 2nd Edition, National Association of Corrosion Engineers, Houston, Texas, 1991.
9. Anon., "Basic Course, Appalachian Underground Corrosion Short Course," West Virginia University, Morgantown, West Virginia, 1985.
10. Romanoff, M., "Corrosion Evaluation of Steel Test Piles Exposed to Permafrost Soils," NBS Papers on Underground Corrosion of Steel Piling, 1962-1971, *National Bureau of Standards Monograph No. 127*, March 1972.
11. Lamb, S. E. and O. E. Picozzi, "Reconstruction of Route 5 Father Baker Bridge, Cities of Buffalo & Lackawana, Erie County," New York State Department of Transportation, Soil Mechanics Bureau & Materials Bureau, PIN 5034.43, D500769, February 1990.
12. Greene, N. D., R. P. Long, J. Badinter, and P. R. Kambala, "Corrosion of Steel Piles," *Corrosion '95*, Paper No. 17, National Association of Corrosion Engineers, 1995.
13. Romanoff, M., "Corrosion of Steel Pilings in Soils," *National Bureau of Standards Monograph 58*, October 1962.
14. U.S. Army Corps of Engineers, "Report on Corrosion of Underground Steel Piling," Engineering Study ES-311, Vicksburg, Mississippi, 1969.

APPENDIX A

Bibliography

BIBLIOGRAPHY

Alberts, D., "Ultrasonic Measurements on Heavily Corroded Steel Pile Walls," HANSA-Schiffahrt-Schiffbau-Hafen Vol. 128, No. 3-4, February 1991, pp. 196-200.

American Association of State Highway and Transportation Officials, "Manual for Condition Evaluation of Bridges," 1994, 136 pages.

American Society for Testing and Materials, "Corrosion Forms and Control for Infrastructure," ASTM STP 1137, 1992, 425 pages.

Balala, B., "Investigation of Corrosion in the Steel H-Piles Supporting the Richmond-SanRafael Bridge," Materials Protection and Performance, Vol. 11, No. 9, 1972, pp. 30-32.

Barker, R.M., J.M. Duncan, K.B. Rojiani, P.S.K. Ooi, C.K. Tan, and S.G. Kim, "Manuals for the Design of Bridge Foundations: Shallow Foundations, Driven Piles, Retaining Walls and Abutments, Drilled Shafts, Estimating Tolerable Movements, and Load Factor Design Specifications and Commentary," NCHRP Report 343, Transportation Research Board, National Research Council, 1991, 320 pages.

Beaton, J.L. and R.F. Stratfull, "Field Test for Estimating Service Life of Corrugated Metal Pipe Culverts," Highway Research Board Proceedings, Vol. 41, 1962, pp. 255-272.

Beaton, J.L. and R.F. Stratfull, "Corrosion of Corrugated Metal Culverts in California," Highway Research Board Bulletin, Report No. 223, 1959, pp. 1-13.

Beckwith, N.R., "Corrosion Test Program of Steel Pipes in River Murray Swampland, South Australia," Corrosion Australasia, Vol. 6, No. 3, June 1981 pp. 11-16.

Beckwith, N.R., "Cathodic Protection of a Pumping Station on the River Murray," Corrosion Australasia, Vol. 5, No. 6, December 1980, pp. 13-15.

Bednar, L., "The Durability of Galvanized Highway Culverts," Proceedings: Performance of Galvanized Products, Chicago, Illinois, American Hot Dip Galvanizers Association, September 1980, 64 pages.

Bellair, P.J. and J.P. Ewing, "Metal-Loss Rates of Uncoated Steel and Aluminum Culverts in New York," Transportation Research Record, No. 1001, Transportation Research Board, National Research Council, 1984, pp. 60-66.

Berg, V.E., "A Culvert Material Performance Evaluation," Washington State Department of Highways, Report No. 0287, April 1965, 73 pages.

Bethlehem Steel, "How Corrosion Affects Steel H-Piles in Earth," Engineering Aids from Bethlehem Steel, December 1977, 2 pages.

Bjerrum, L., "Norwegian Experience with Steel Pile Foundations to Rock," Journal of the Boston Society of Civil Engineering, Vol. 44, No. 3, July 1957, pp. 155-198.

Booth, G.H., A.W. Cooper, P.M. Cooper, and D.J. Wakerley, "Criteria of Soil Aggressiveness Towards Buried Metals," British Corrosion Journal, Vol. 2, May 1967, pp. 104-108.

Brady, K.C. and W. McMahon, "The Durability of Corrugated Steel Buried Structures," Transport Research Laboratory, No. PR 1, 1993, 47 pages.

Braunton, P.N. and W.R. Middleton, "Assessment of the Corrosion of Mild Steel in Reinforced Earth Structures Backfilled with Pulverized Fuel Ash," Proceedings: AshTech '84 - International Conference on Ash Technology and Marketing, London, UK, Central Electricity Generating Board, 1984, pp. 535-542.

Bushman, J.B., C.L. Tracy, and W.F. Rogers, "Condition and Corrosion Survey on Corrugated Steel Storm Sewer and Culvert Pipe, Second Interim Report," Corrpro Companies, Incorporated, September 1988, 84 pages.

Camitz, G., et al., "Cathodic Protection of Sheet Steel Piling in Fresh Water," Proceedings: 7th Scandinavian Corrosion Congress, Trondheim, 1975, pp. 334-345.

Chaker, V. and D. Lindemuth, "Stray Currents – A Case Study The New York City World Trade Center," Corrosion '89 Paper No. 234, National Association of Corrosion Engineers, 1989, 25 pages.

Chaker, V. and D.D. Lindemuth, "The State of the Art in Corrosion Protection of Marine Piles," Corrosion '90 Paper No. 376, National Association of Corrosion Engineers, 1990, 16 pages.

Chaker, V., "A Call to Action on the Corrosion of Steel Pilings in Soil," Materials Performance, Vol. 32, No. 10, October 1993, pp. 30-33.

Chaker, V., "Steel Piling May Be in Trouble," ASTM Standardization News, Vol. 21, No. 5, American Society for Testing and Materials, 1993, pp. 30-33.

Chandler, B.C. and J.G. Cannon, "Geotechnical Aspects of the Bell Bay Anchored Retaining Wall," Proceedings: 4th Australia-New Zealand Conference on Geomechanics, Perth, Australia, Vol. 1, No. 84/2, Institute of Engineers, Australia, 1984, pp. 294-299.

Colorado Department of Highways, "Culvert Performance at Test Sites in Colorado," Report No. 68-8, Federal Highway Administration, August 1968, 15 pages.

Cornfield, G.M., "Steel Bearing Piles," Transport and Road Research Laboratory, Monograph, Constrado, October 1980, 44 pages.

Crocombe, C.A. and D.M. Wilson "Piling Experience in the Melbourne Area," Institution Engineers Journal, Australia, Vol. 39, No. 6, pp. 83-93.

Crompton, A.C. and W. Brown, "Corrosion Prevention of Steel Piles and Footings for Elevated Roadways and Bridge Abutments," Proceedings: Australian Road Research Board Conference, Vol. 3, Part 2, Paper No. 294, Road Research Laboratory, 1966, pp. 1636-1641.

Dana, J.S. and R.J. Peters, "Corrosion of Highway Structures," Transportation Research Record, No. 539, Transportation Research Board, National Research Council, 1975, pp. 27-37.

Darbin, M., J.M. Jailloux, and J. Montuelle, "Durability of Reinforced Earth Structures: The Results of a Long-Term Study Conducted on Galvanized Steel," Proceedings: Institution of Civil Engineers, Part 1, October 1988, pp. 1029-1057.

de Rincon, O.T. "Experiences with Sacrificial Anodes for Protection of the Pilings of the General Rafael Urdaneta Bridge Over Lake Maracaibo," Corrosion '85, Paper No. 260, National Association of Corrosion Engineers, 1985, 20 pages.

Deaton III, H., "Tieback Wall Stabilization of Railroad Embankments," Transportation Research Record, No. 1030, Transportation Research Board, National Research Council, 1985, pp. 29-37.

DeMarco, R.C., "Protection of Underground Steel in a Highly Corrosive Area," Materials Protection, Vol. 3, No. 2, February 1964, pp. 42-45.

Diusmuke, T.D., et al., "Handbook of Corrosion Protection for Steel Pile Structures in Marine Environments," American Iron and Steel Institute, 1981, 245 pages.

Dively II, R.W., "Corrosion of Culverts," Materials Performance, Vol. 31, No. 12, December 1992, pp. 47-50.

Doran, S.R., P. Robery, H. Ong, and S.A. Robinson, "Corrosion Protection to Buried Structures," Transport and Road Research Laboratory, Vol. 1, No. 2, Scientific and Technical Press Limited, June 1987, pp. 88-97.

Drabble, J.R., "Corrosion of Zinc Coated Steel Culverts," Corrosion Australasia, December 1976, pp. 16-21.

Eadie, G.R., "Corrosion of Steel Piling - Results from a Test at Burnley, Victoria," SEAISI Q., Vol. 7, No. 4, October 1978, pp. 34-40.

Edgar, T.V., "In-Service Corrosion of Galvanized Culvert Pipe," ASTM STP 1013, American Society for Testing and Materials, 1989, pp. 133-143.

Elias, V., "Durability/Corrosion of Soil Reinforced Structures," U. S. Department of Transportation, Report No. FHWA-RD-89-186, December 1990, 163 pages.

Escalante, E., W.P. Iverson, W.F. Gerhold, B.T. Sanderson, and R.L. Alumbaugh, "Corrosion and Protection of Steel Piles in a Natural Seawater Environment," National Bureau of Standards, Monograph No. 158, June 1977, 36 pages.

Escalante, E., "Measuring the Underground Corrosion of Steel Piling at Turcot Yard, Montreal, Canada – A 14 Year Study," ASTM STP 1137, American Society for Testing and Materials, 1992, pp. 339-355.

Fischer, K.P. and B. Bue, "Corrosion and Corrosivity of Steel in Norwegian Marine Sediments," ASTM STP 741, American Society for Testing Materials, 1981, pp. 24-32.

Gadsby, W.P., "The Corrosion of Galvanized Steel Culverts," Proceedings: 7th Conference of the Australian Road Research Board, Vol. 7, No. 7, Australian Road Research Board, Vermont, Victoria, 1975, pp. 309-325.

Garanin, L.I. and V.N. Kushnir, "The Corrosion Protection of Steel Piles in Industrial Plant," Nefti Gaza Tyumeni (Tyumen), No. 45, 1980, pp. 56-57.

Garber, J.D., J.H. Lin, and L.G. Smith, "Feasibility of Applying Cathodic Protection to Underground Culverts, Interim Report," Louisiana Department of Transportation, Report No. FHWA/LA-91/238, Federal Highway Administration, 1991, 178 pages.

Girnau G., et al., "Underground Traffic and Construction, No. 14: Construction, Corrosion and Corrosion Protection of Underground Steel Framework: Sheet Piling, Tubbing, Belches," Alba-Buchverlag, 1973, 183 pages.

Greene, N.D., R.P. Long, J. Badinter, and P.R. Kambala, "Corrosion of Steel Piles," Corrosion '95, Paper No. 17, National Association of Corrosion Engineers, 1995, 11 pages.

Greulich, G.G., "Extracted Steel H-Piles Found in Good Condition," Engineering News-Record, Vol. 145, No. 8, August 1950, pp. 41-42.

Haviland, J.E., P.J. Bellair, and V.D. Morrell, "Durability of Corrugated Metal Culverts," New York State Department of Transportation, Interim Report No. 66-5, 1967, 84 pages.

Heffern, P.M., "Review and Implementation of Ohio Culvert Durability Study," Concrete Pipe News, Vol. 35, No. 3, June 1982, pp. 5-12.

Hein, W., "Corrosion of Steel Piling Walls in Water," HANSA-Schiffahrt-Schiffbau-Hafen, Vol. 126, No. 3-4, 1989, pp. 250-253.

Hildebrand, V.H. and W. Schwenk, "Investigations on Corrosion of Unprotected Steel in Soils with and without Cell Formation," Werkstoffe und Korrosion, Vol. 29, No. 2, February 1978, pp. 92-97.

Holt, A.R., "Durability Design Method for Galvanized Steel Pipe in Minnesota," National Corrugated Steel Pipe Association, 1967, 34 pages.

Holt, J.D., and R.A. Douglas, "A Field Test Procedure for Finding the Overall Lengths of Installed Timber Piles by Dispersive Wave Propagation Methods," The University of North Carolina Institute for Transportation Research and Education, Report No. NC/R&D/94-001, March 1994, 48 pages.

Hoshino, K. and M. Abe, "Corrosion of Foundation Steel Piling and its Cathodic Protection," Corrosion Engineering, Vol. 15, No. 7, 1966. pp. 304-308.

Hoshino, K., "Electrolysis of Steel Piles Caused by Stray Current," Corrosion Engineering, Vol. 13, No. 7, July 1964, pp. 309-312.

Howard Jr., J.D. and M. Ali, "Corrosion Investigation of Steel H-Piles," Corrosion '90 Paper No. 414, National Association of Corrosion Engineers, 1990, 13 pages.

Hurd, J.O., "Field Performance of Protective Linings for Concrete and Corrugated Steel Pipe Culverts," Transportation Research Record, No. 1001, Transportation Research Board, National Research Council, 1984, pp. 35-40.

Hurd, J.O. and S. Sargand, "Field Performance of Corrugated Metal Box Culverts," Transportation Research Record, No. 1191, Transportation Research Board, National Research Council, 1988, pp. 39-45.

James, L.M., "Unexpected Corrosion of Galvanized Corrugated Metal Culverts," Australian Road Research Board Conference Proceedings, Vol. 4, Part 2, 1968, pp. 1409-1416.

Jerbo, A., "Underground Corrosion of Steel Piles," Proceedings: 5th Scandinavian Corrosion Congress, Vol. 2, October 1968, pp. 26.2-26.10.

Kano, R.Y. Sone, I. Yamamoto, and N. Nakatani, "Development of Monitoring System for Steel Pipe Piles," Bosei Kanri, Vol. 36, No. 10, 1992, pp. 361-370.

Kasahara, K., H. Adachi, and F. Kajiyama, "Corrosion of Buried Steel Pipes Driven by Macro-Galvanic Cells," Proceedings: 7th Congress of the European Federation of Corrosion, September 1981, pp. 1832-1837.

Kawai, Y., S. Nakamura, and T. Tanaka, "Residual Strength Evaluation of Corroded Structural Steel Members," EVALMAT '89 Proceedings: International Conference on Evaluation of Materials Performance in Severe Environments, Vol. 1, Iron and Steel Institute of Japan, November 1989, pp. 407-414.

Kinchen, R.W., "Evaluation of the Durability of Metal Drainage Pipe," Transportation Research Record, No. 762, Transportation Research Board, National Research Council, 1980, pp. 25-32.

Kinchen, R.W., W.H. Temple, H.W. Lacinak, and B.J. Gueho, "Evaluation of Drainage Pipe by Field Experimentation and Supplemental Laboratory Experimentation, Interim Report," Louisiana Department of Transportation, Report No. FHWA/LA-78/115, Federal Highway Administration, March 1978, 60 pages.

King, R.A., "Review of Soil Corrosiveness with Particular Reference to Reinforced Earth," Department of Transportation, Transport and Road Research Laboratory Supplementary Report No. 326, Crowthorn, Berkshire, 1977, 29 pages.

Kinson, K. and G.R. Eadie, "Microbial Corrosion of Steel Piling," Chemical Industries (London), No. 13, 1980, 518 pages.

Kita, D. and M. Moriya, "Studies on Underground Water Pollution and the Corrosion of Steel Pipe Piles Caused by Chemical Waste Liquor," Obayashi-Gumi Gijutsu Kenkyusho-ho, Vol. 7, 1973, pp. 122-127.

Lamb, S.E. and O.E. Picozzi, "Pile Corrosion Evaluation," Soil Mechanics & Materials Bureaus, PIN 5034.43 D500769, State of New York Department of Transportation, February 1990, 14 pages.

Lawson, K.M., N.G. Thompson, M. Islam, and M.J. Schofield, "Monitoring Corrosion of Reinforced Soil Structures," British Journal of Non-Destructive Testing, V. 35, No. 6, June 1993, pp. 319-324.

Leatham, J.L. and G.E. Peterson, "Pipe Selection for Corrosion Resistance," Utah Department of Transportation, Report No. UDOT-IMP-76-1, Research and Development Section, January 1977, 36 pages.

Lee, R.U. and A.H. Clark, "Corrosion of Steel Pilings in Soil," Corrosion '93 Paper No. 6, National Association of Corrosion Engineers, March 1993, 12 pages.

"Long Exposure Underground has Little Effect on Steel Pilings," Materials Protection, Vol. 1, No. 12, December 1962, pp. 45, 47.

Long, R.P. and S. Lele, "In Situ Detection of Pile Corrosion," Connecticut Department of Transportation, Report No. JHR 92-207, Connecticut Department of Transportation, April 1992, 74 pages.

Long, R.P. and F. Huang, "Corrosion of Driven Steel Piles," Connecticut Department of Transportation, Report No. JHR 90-193, Connecticut Department of Transportation, May 1990, 41 pages.

Long, R.P., "Corrosion of Steel Piles in Some Waste Fills," Transportation Research Record, No. 1345, Transportation Research Board, National Research Council, 1992, pp. 53-59.

Long, R.P., J. Badinter, and P.R. Kambala, "Investigation of Steel Pile Foundations in Corrosively Active Areas," Connecticut Department of Transportation, Report No. JHR 95-239, Connecticut Department of Transportation, March 1995, 135 pages.

McClintock, R., A. Singh, and A. Smith, "Field Tests of a System for Underwater Inspection of Corroded Steel Pilings," Review of Progress in Quantitative Nondestructive Evaluation, Vol. 3B, Plenum Press, 1984, pp. 1417-1424.

McDermott, J.F., "All-Steel Abutments for Highway Bridges," Civil Engineering, Vol. 33, No. 2, February 1963, pp. 54-56.

Moody, W.P., "Corrosion in the Soil Environment: New York's Experience," New York State Department of Transportation Soil Mechanics Bureau, April 1993, 19 pages.

Morley, J., "A Review of the Underground Corrosion of Steel Piling," Steel Construction, Vol. 13, No. 4, July 1989, pp. 13, 16-18.

Morris, G.E. and L. Bednar, "Comprehensive Evaluation of Aluminized Steel Type 2 Pipe Field Performance (Discussion and Closure)," Transportation Research Record, No. 1001, Transportation Research Board, National Research Council, 1984, pp. 49-60.

National Bureau of Standards, "Steel Pilings in Soils," Dimensions, Vol. 55, No. 5, 1971, p. 120.

Noyce, R.W., R.W. Ostrowski, and J.M. Ritchie, "Corrosion of Galvanized Metal Culverts," Transportation Research Record, No. 539, Transportation Research Board, National Research Council, 1975, pp. 38-49.

Noyce, R.W. and J.M. Ritchie, "Michigan Galvanized Metal Culvert Corrosion Study," Transportation Research Record, Report No. 713, Transportation Research Board, 1979, pp. 1-6.

Ohsaki, Y., "Corrosion of Steel Piles Driven in Soil Deposits," Soils and Foundation, Vol. 22, No. 3, Japanese Society of Soil Mechanics and Foundation Engineers, September 1982, pp. 57-76.

Okamoto, K., "Tests on Corrosion and Cathodic Protection of Steel Pilings in Soils," Corrosion Engineering, Vol. 14, No. 9, September 1965, pp. 9-13, 393-397.

Patenaude, R., "Microbial Corrosion of Culvert Pipe in Wisconsin," Proceeding: Biologically Induced Corrosion, Gaithersburg, Maryland, National Association of Corrosion Engineers, June 1985, pp. 92-95.

Patenaude, R., "Bacterial Corrosion of Steel Culvert Pipe in Wisconsin," Transportation Research Record, No. 1001, Transportation Research Board, National Research Council, 1984, pp. 66-69.

Patenaude, R., "Corrosion Evaluation of Culvert Pipe in Wisconsin," Wisconsin Department of Transportation, Progress Report No. 5, 1981, 38 pages.

Peng, C.G., J.K. Park, and R.W. Patenaude, "Prediction of Metal Culvert Corrosion Rate Influenced by Microorganisms," Proceeding: Microbial Influenced Corrosion, Institute of Applied Microbiology, University of Tennessee, 1990, pp. 8/23-8/25.

Picozzi, O.E., S.E. Lamb, and A.C. Frank, "Evaluation of Prediction Methods for Pile Corrosion at the Buffalo Skyway," New York State Department of Transportation Technical Services Division, February 1993, 35 pages.

Porter, G., "Monitoring Corrosion in the Field," NBS Dimensions, Vol. 63, No. 11, 1979, pp. 3-9.

Pye, E.L. and F.H. Brock, "Prediction of Remaining Zinc on a Buried Culvert from Polarization Measurements," Materials Performance, Vol. 17, No. 10, October 1978, pp. 19-21.

Pyskadlo, R.M. and J.P. Ewing, "Coatings for Corrugated Steel Pipe, Final Report," New York State Department of Transportation, Report No. FHWA/NY/SR-87, Engineering Research and Development Bureau, 1987, 41 pages.

Pyskadlo, R.M., "Performance of Polymer-Coated and Bituminous-Coated-and-Paved Corrugated Steel Pipe, Final Report," New York State Department of Transportation, Report No. FHWA/NY/SR-89/94, Federal Highway Administration, May 1989, 22 pages.

Ramaswamy, S.D. and S.K. Roy, "The Importance of Evaluating Subsoil Corrosion and its Effects on Buried Structures," Transport and Road Research Laboratory, pp. 325-334.

Rogers, P.J. and R.R. Johnston, "Bacterial Corrosion of Steel," Proceedings: 12th Annual Conference Australasian, Vol. 5, Australasian Corrosion Association, 1972, pp. 5.1-5.13.

Romanoff, M., "Performance of Steel Pilings in Soils," NBS Papers on Underground Corrosion of Steel Piling, 1962-1971, NBS Monograph No. 127, National Bureau of Standards, March 1972, pp. 31-39.

Romanoff, M., "Corrosion Evaluation of Steel Test Piles Exposed to Permafrost Soils," NBS Papers on Underground Corrosion of Steel Piling, 1962-1971, NBS Monograph No. 127, National Bureau of Standards, March 1972, pp. 23-30.

Romanoff, M., "Corrosion of Steel Pilings in Soils," National Bureau of Standards Journal of Research, Vol. 66C, No. 3, 1962, pp. 223-224.

Sandegren, E., "Final Report about Corrosion of Steel, Test Place: Stockholm Central Station," SJ Geoteknik och Ingenjoersgeologi Meddelanden, No. 45, Statens Jaernvaegar, Centralfoervaltningen, 1985, 25 pages.

Satomi, T., et al., "Monitoring of Tank Corrosion and Change in Properties of Foundation Soil," Corrosion '88 Paper No. 420, National Association of Corrosion Engineers, 1988, 13 pages.

Sawaguchi, M., "Applications of Steel Pipe Piles in Japan," Geotechnical Engineering, Vol. 10, No. 2, 1979, pp. 199-218.

Schliebaum, R., "Hot Dip Galvanizing is Also Effective in Bridge Construction," Verzinken, Vol. 5, No. 1, 1976, pp. 21-22.

Schwerdtfeger, W.J. and M. Romanoff, "NBS Papers on Underground Corrosion of Steel Piling 1962-1971," National Bureau of Standards, March 1972, 63 pages.

Schwerdtfeger, W.J. and M. Romanoff, "Corrosion Rates on Underground Steel Test Piles at Turcot Yard, Montreal, Canada. Pt. 1," NBS Monograph 128, National Bureau of Standards, July 1972, 13 pages.

Schwerdtfeger, W.J., "Polarization Measurements as Related to Corrosion of Underground Steel Piling," Journal of Research Engineering and Instrumentation, Vol. 75C, No. 2, 1971, pp. 107-121.

Scranton Gillette Communications, "OHare Bridge to Carry Aircraft Over Highway," Roads and Bridges, Vol. 25, No. 11, Incorporated, November 1987, pp. 56-57.

Singh, A. and R. McClintock, "Underwater Tests on Corroded Steel Piles with the Thickness Measurement by Beam Alignment System," Journal of Energy Resources Technology, Transactions of the ASME, Vol. 106, No. 2, American Society of Mechanical Engineers, June 1984, pp. 257-259.

Slavid, R., "Made-Up Ground - The Need for Thorough Site Investigation," Construction in Southern Africa, Vol. 27, No. 11, Pithead Press Limited, February 1983, p. 47.

Smith, D.D., "The Effectiveness of Horizontal Drain," California Department of Transportation, Report No. FHWA/CA/TL-80/16, FCP 4084-633, June 1980, 79 pages.

Stanley, M.T., "Evaluation of a Galvanic Anode System for Bridge Piles," North Carolina Department of Transportation, Construction Report, May 1991 - April 1992, Project No. 170-3C, North Carolina Department of Transportation, July 1992, 5 pages.

State of California Department of Transportation, "Method for Estimating the Service Life of Steel Culverts," California Test 643, 1993, 10 pages.

Stavros, A.J., "Galvalume Corrugated Steel Pipe: A Performance Summary," Transportation Research Record, No. 1001, Transportation Research Board, National Research Council, 1984, pp. 69-76.

Stratful, R.F., "Highway Corrosion Problems Metallic Culverts and Reinforced Concrete Bridges," Materials Protection, Vol. 2, No. 9, September 1963, pp. 8-12, 14.

Stratfull, R.F. and C. Seim, "Corrosion of Steel Piles at the Richmond-San Rafael Bridge," California State Department of Transportation, Report No. TL-627137, June 1979, 53 pages.

Stratfull, R.F., "A New Test for Estimating Soil Corrosivity Based on Investigation of Metal Highway Culverts," Corrosion, Vol. 17, Part 2, October 1961, pp. 493t-496t.

Stratton, F.W., J.A. Frantzen, and D.A. Meggers, "Cause of Accelerated Deterioration of Corrugated Metal Pipe Installed after 1974," Kansas Department of Transportation, December 1990, 16 pages.

Swanson, H.N. and D.E. Donnelly, "Performance of Culvert Materials in Various Colorado Environments," Colorado Department of Highways, Report No. FHWA-CO-77-7, FCP 45C3154, Planning and Research Section, September 1977, 28 pages.

Takihara, M. and A. Osakai, "Prevention of Corrosion by Stray Currents," Corrosion Engineering, Vol. 17, No. 1, 1968, pp. 18-23.

Tanaka, H., "Long Term Corrosion Tests of Steel Piles Driven in Soil," Proceedings: 11th International Corrosion Congress, Florence Italy, Vol. 5, Associazione Italiana Di Metallurgia, April 1990, pp. 5.179-5.186.

Temple, W.H. and S.L. Cumbaa, "Evaluation of Metal Drainage Pipe Durability after Ten Years," Transportation Research Record, No. 1087, Transportation Research Board, National Research Council, 1986, pp. 7-14.

Temple, W.H., S.L. Cumbaa, and B.J Gueho, "Evaluation of Drainage Pipe by Field Experimentation and Supplemental Laboratory Experimentation," Louisiana Department of Transportation and Development, Report No. FHWA-LA-85-174, March 1985, 51 pages.

Timmerman, D.H., "Evaluation of Mechanically Stabilized Embankments as Support for Bridge Structures, Final Report," Ohio Department of Transportation, Report No. FHWA/OH-91/014, Federal Highway Administration, 1992, 80 pages.

Tomashov, N.D. and Y.N. Mikhailovsky, "Corrosivity of the Soil," Corrosion, Vol. 15, February 1959, pp. 77t-82t.

Transportation Research Board, "Culvert Corrosion, Porous Lane Marking, Membranes, Polymer Concrete, and Reflectometer Evaluations," Transportation Research Record, No. 713, Transportation Research Board, National Research Council, 1979, 30 pages.

Transportation Research Board, "Culvert Distress and Failure Case Histories and Trenchless Technology," Transportation Research Record, No. 1431, National Research Council, 1994, 82 pages.

Transportation Research Board, "Symposium on Durability of Culverts and Storm Drains," Transportation Research Record, No. 1001, National Research Council, 1984, 125 pages.

United States Army Corps of Engineers, "Report on Corrosion of Underground Steel Piling," USACE-Lower Mississippi Valley District, Engineering Study ES-311 December 1969, 33 pages.

"Useful Life of Steel Piles in Soil," International Construction, Vol. 12, No. 1, January 1973, pp. 26-27.

Vesic, A.S., "Design of Pile Foundations," NCHRP Synthesis of Highway Practice, No. 42, Transportation Research Board, National Research Council, 1977, 68 pages.

VETEK Systems Corporation, VETEK V2000 Corrosion Monitoring System, product literature, 6 pages.

Wietek, B., "A Permanent Monitoring System for Permanent Anchors Using Installed Electrodes," XLII Geomechanik-Kolloquium, Salzburg, Austria, October 1993, 15 pages.

Winters, W.R., "Non-Destructive Testing Protects Nation's Marine Industry," Materials Evaluation, Vol. 22, No. 8, August 1964, pp. 361-362.

Wilson, D.M., R.R.M. Johnson, and C.P. Lloyd, "Piling Investigation at West Melbourne," Australasian Corrosion Association, Conference No. 14, 1973, 21 pages.

Wolfe, V.D. and S.H. Macnab, "Corrugated Metal Pipe Comparison Study, Final Report," Oregon Department of Transportation, Report No. FHWA-OR-76-3, Federal Highway Administration, July 1976, 97 pages.

Worley, H.E., "Corrosion of Corrugated Metal Pipe," Kansas State Highway Commission, 1971, 13 pages.

Worley, H.E., "Effectiveness of Bituminous Coatings on Corrugated Metal Pipe," Department of Planning and Development, Research Division, State Highway Commission of Kansas, 1989, 9 pages.

Yamamoto, K., H. Nakamura, and K. Kudocey, "Investigation on Corrosion of Steel Structures for Civil Engineering at Thermal Power Station," Central Research Institute of Electric Power Industry (Japan), October 1989, 65 pages.

Young, F.E., et al., "Piles and Foundations," Monograph, Thomas Telford Limited, 1981, 329 pages.

APPENDIXES B AND C

Appendix B, "Task 1 Questionnaire," and Appendix C, "Database of Questionnaire Responses," are not published herein. Copies may be obtained on request to NCHRP.

APPENDIX D

State-of-the-Art Survey of Piling Corrosion

APPENDIX D

State-of-the-Art Survey of Piling Corrosion

Case Histories

Case histories of documented incidences of significant corrosion of steel piling were compiled in Task 2. These case histories are given at the end of this appendix, following the references. This is not purported to be an all-inclusive listing of incidences, although all examples of significant piling corrosion found in the literature are included. Significant corrosion is arbitrarily defined as a general loss of greater than 15% of the thickness of the piling at any single location. Isolated pitting is excluded from the criterion and this pitting is usually deeper than 15% of the thickness. The case histories are organized chronologically, starting with the most recent examples.

Table D-1 is a summary of these case histories. All of the incidences of corrosion in Table D-1 occurred in disturbed fill soils. In all cases, the soils were layered and the attack was confined to one of the layers. This behavior is consistent with a differential aeration cell mechanism for the attack. The highest corrosion rates reported generally occurred in man-made products such as ash, slag, and cinders. With the exception of the Sardis Dam Outlet, the attack also occurred at or above the water table. The piles at the Sardis Dam Outlet were examined in October (1959) and it is possible that the water table was unusually high at that time. With the exception of the Grenada Dam Spillway, the soils also would be classified as corrosive based on their resistivity, their pH or both. It is interesting to note that a layer of soil immediately above the corrosive layer at the Grenada Dam Spillway had a pH of 4.4, which is two units lower than the value recorded for the most corrosive layer.

The case histories described in Table D-1 are all examples of soil corrosion of pilings. Corrosion of pilings in fresh water above the ground level also is a problem, as described above. Attack in fresh water can be more severe than attack in soil, especially where the water level fluctuates. For example, the exposed portion of the piling in the Lumber River that experienced a 40% thickness loss in the soil experienced a 76% loss in the river water.

Further details on the soil conditions causing corrosion are given below.

Mechanism of Piling Corrosion

A general definition of corrosion is the degradation of a material through environmental interaction. This definition encompasses all materials, both naturally occurring and man made, and includes plastics, ceramics, and metals. All commonly used engineering metals, such as steel, corrode because they are thermodynamically unstable. One principle of thermodynamics is that a material always seeks the lowest energy state. A significant amount of energy is put into a metal when it is extracted from its ores, placing it in a high energy state. In the corrosion process, the energy of the metal is reduced as it reverts to a corrosion product, which in many cases is an ore such as hematite.

Corrosion of metals in aqueous (water containing) environments, such as in soils, is almost always electrochemical in nature. The metal atoms are oxidized (lose electrons) and species such as water, protons, or oxygen are reduced (gains electrons). The metal ions generated by the oxidation of the metal normally then react with water or other species in the environment to create oxides, hydroxides, and other corrosion products. In the case of steel, these products of corrosion are what we call rust. Products also are created by the reduction reactions. These products include hydroxide and hydrogen. A summary of typical reactions for the corrosion of steel is given below.

Table D-1.   Summary of Case Histories Of Significant Corrosion Of Pilings.

Location	Age (years)	Original Thickness (inches)	Minimum Thickness (inches)	Thickness Loss (inches)	Thickness Loss (percent)	One-Side Corrosion Rate (mpy)	Soil Type	Location With Respect To Water Table	pH	Resistivity (ohm-cm)	Chlorides (ppm)	Sulfates (ppm)	References
Sweet Home Road, Buffalo, NY	7.	-	-	-	-	*	Cinders/Clay	Poorly Drained	-	-	-	-	1
Father Baker Bridge, Buffalo, NY	32.	0.436	0.297	0.139	31.9	2.17	Silt/Slag/Cinders	At or Near	9.0-9.3	733-1133	223-267	115-176	2
I84/I91 Interchange, Hartford, CT	29.	0.375	0.131	0.244	65.1	4.21	Clay/Coal/Ash	Above	3.8	380	-	-	3, 4
Sparrows Point, MD	18.	0.55	0.39	0.16	29.1	4.44	Sand/Slag/Cinders	At Water Table	3.7	1130-4000	-	-	5
Lumber River, Boardman, NC	37.	0.26	0.156	0.104	40.0	1.41	Fine Sandy Loam	0 to 3' Below	3.4	1240	-	-	5
Sardis Dam Outlet, Sardis, MS	20.5	0.375	0.304	0.071	18.9	1.73	Riprap/Gravel	5' Below	3	610	-	-	5
Grenada Dam Spillway, Grenada, MS	11.4	0.375	0.304	0.071	18.9	3.11	Silty Sand	Above	6.4	4000	-	-	5

* Moderate-to-heavy section loss.

Oxidation of Iron	$Fe \rightarrow Fe^{+++} + 3e^-$	(1)
Oxygen Reduction	$O_2 + 2H_2O + 4e^- \rightarrow 4OH^-$	(2)
Water Reduction	$2H_2O + 2e^- \rightarrow H_2 + 2OH^-$	(3)
Hydrogen Ion Reduction	$2H^+ + 2e^- \rightarrow H_2$	(4)
Formation of Rust	$2Fe^{+++} + 3H_2O \rightarrow Fe_2O_3 + 6H^+$	(5)

There are many other possible corrosion products in soil environment, including magnetite (Fe_3O_4), iron hydroxide ($Fe(OH)_3$), and various carbonates and sulfates. The composition of the corrosion products is dependent on the species present in the environment. For example, the corrosion products are dominated by reduced (lower oxidation state) iron species such as magnetite where oxygen is not present.

Because the common engineering metals are thermodynamically unstable in natural environments, the useful life of an engineering structure is determined by the rate of corrosion, referred to as the corrosion kinetics. The corrosion kinetics can be controlled by the rate of the oxidation reaction, the rate of the reduction reaction, or current flow between the locations on the metal surface where the two reactions are occurring. For example, oxide films may form on the metal surface that are tenacious and protective, limiting the rate of metal oxidation. Stainless steels and aluminum are corrosion resistant in many environments because they form thin protective oxide films. Carbon steels also form protective oxide films in elevated pH and in some carbonate environments.

The rate of general corrosion of carbon steels is usually limited by the rate of the reduction reaction. In the case of underground corrosion of steels, oxygen reduction is the dominant reduction reaction controlling the corrosion rate. In this environment, pH values are not normally low enough for hydrogen ion reduction to be significant and the rates of water reduction are low. For the oxygen reduction reaction, the rate controlling process is generally the diffusion of oxygen through the soil or electrolyte to the metal surface. This rate is controlled by the concentration of oxygen in the soil and the thickness of the water layer through which the oxygen must diffuse. The most severe conditions are generally those where a thin water layer is present on the metal surface, providing a short diffusion path for the oxygen. These conditions are normally encountered in moist, but not saturated porous soils, especially in zones that are alternately wet and dry due to fluctuations of the water table.

The electrochemical reactions can occur uniformly on a metal surface, leading to a general corrosion of the metal. At one instant in time, metal oxidation may be occurring at a location, while one of the reduction reactions may occur at the same instant on an adjacent atom, consuming the electrons liberated by the metal oxidation reaction. An instant later, the location of the reactions may switch. For most underground steel structures, rates of general corrosion are usually low and can be predicted. Therefore, general corrosion rarely causes service failures.

It is also possible for the oxidation and reduction reactions to be separated on a metal surface, where the metal oxidation occurs predominantly at one site while the reduction reaction occurs predominantly at another site. This is referred to as a macrocell. One type of macrocell is a differential aeration cell, shown schematically in Figure D-1. The differential aeration cell is probably the most common corrosion cell that is experienced on pilings, pipelines, and other types of underground structures. The site where net oxidation occurs is called the anode and the site where net reduction occurs is called the cathode. In the metal, the electrons liberated by the oxidation reaction flow from the anode to the cathode where they are consumed by the reduction reaction. In the soil, electrical (positive) current, in the form migrating ions, must flow from the anode to the cathode to maintain charge neutrality. The current flows through the aqueous phase in pore spaces between the soil particles.

In general, macrocells are especially insidious in that, once the oxidation and reduction reactions become separated, the electrochemical reactions create local environments that exacerbate the attack. For example, the reduction reactions cause an increase in the electrolyte pH at the cathode. Steels form tenacious protective
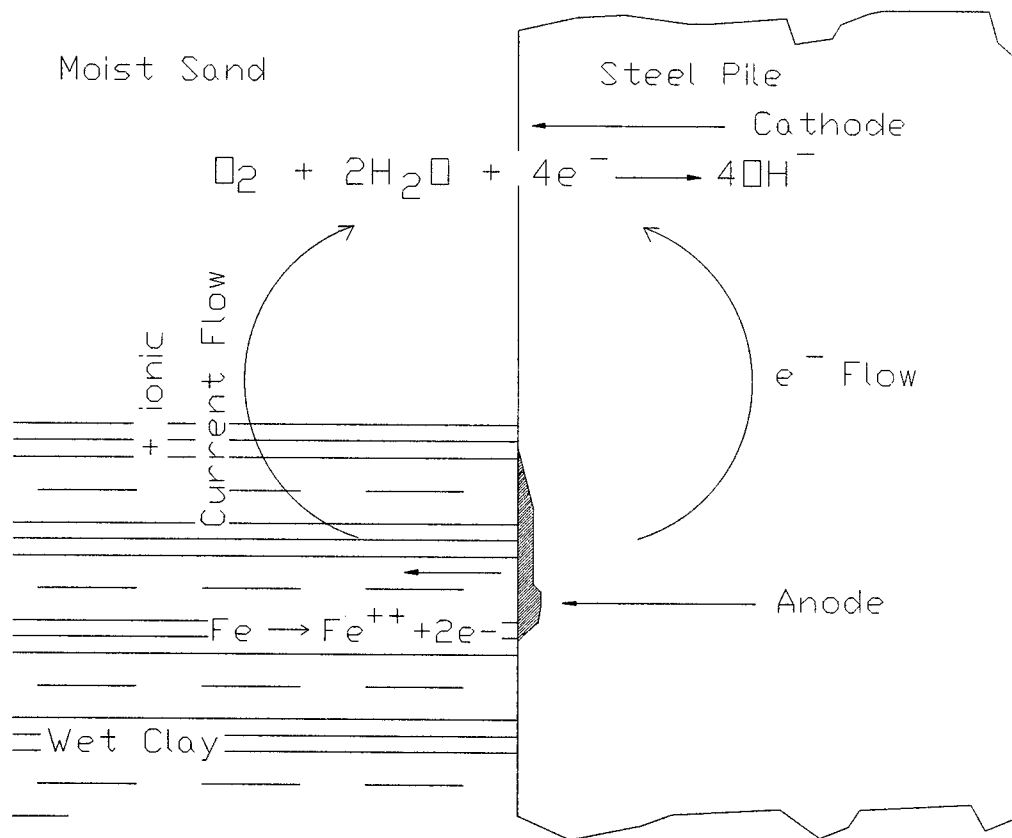
Figure D-1.   Schematic Showing Differential Aeration Cell.

films in elevated pH environments. Therefore, the rate of metal oxidation at the cathode is reduced. On the other hand, hydrolysis of the iron atoms at the anode creates hydrogen ions that reduce the electrolyte pH. The low-pH, acidic environment created at the anode destabilizes any oxide films that may have been present, increasing the rate of attack. As the pH at the anode decreases, the direct reduction of hydrogen ions may occur locally, further increasing the rate of attack.

Factors that affect the rate of differential aeration corrosion include the relative area ratio of the anode and the cathode, soil resistivity and stratification of the soil. Where the cathode is large and the anode is small, a larger current is supported by the cathode and that current is concentrated at the anode, leading to high rates of attack at the anode. Where the soil resistance is high, a high current flow between the anode and cathode cannot be supported due to the high voltage (IR) drop in the high resistance soil path. The maximum separation distance of the anodes and cathodes also is limited by a high soil resistance. Stratification of the soil creates ideal conditions for the development of the differential aeration cells. Oxygen deficient layers, such as wet clays or regions below the water table, become the anodes while oxygen rich layers, such as porous sands, become the cathodes. Further discussion of the effects of resistivity and other parameters on corrosion is given below.

Factors Controlling Piling Corrosion

Position of Water Table

The position of the water table with respect to the pile is probably the most important factor affecting corrosion of steel piling. Little evidence of corrosion has been found where the entire piling is below the water table or where a concrete piling cap extends below the water table, even in corrosive soils. This was one of the major conclusions of the original NBS work by Romanoff[5] and that conclusion has stood the test of time. A recent example is described by Picozzi.[6] An investigation was conducted on steel H-piles in an industrial waste environment in conjunction with rehabilitation of the Buffalo Skyway. The water table was above the concrete pile cap. In spite of the presence of disturbed fill soils and corrosive soil characteristics, little corrosion loss of the piles was detected.

Mechanistically, the effect of water table position on corrosion is readily explained. As described above, most instances of severe underground corrosion are the result of differential aeration cells. Where the entire structure is below the water table, oxygen concentrations near the piling are low and the differential aeration cells do not develop. The dissolved oxygen content in an aqueous phase is only 8 ppm as compared with 20% (200 000 ppm) in the atmosphere.

The position of the water table also may influence piling corrosion in instances where the water table is below the top of the pile. In one Army Corp of Engineers Report,[7] it was observed that corrosion attack of pilings was low where the majority of the piling was located below the water table, even when the region above the water table was in corrosive soils. Again this behavior can be explained based on a differential aeration cell mechanism. With a corrosion cell, the most severe attack occurs where the cathode (oxygen-rich area) is large and the anode (oxygen-deficient area) is small. This would represent conditions where most of the piling is above the water table.

Soil Moisture Content

Fully saturated soil below the water table is one extreme in soil moisture content. The other extreme is dry soil. In the case of general corrosion, there is a maximum in soil corrosivity at an intermediate moisture content. At low moisture contents, there is insufficient water to support the corrosion process while, at high moisture contents, oxygen is excluded from the metal surface and corrosion rates are low.[8] A pile located below the water table is representative of the latter situation.

Macrocell corrosion also cannot occur at very low moisture contents. However, macrocells can operate at high moisture contents where stratified soils are present and oxygen can reach the metal surfaces in one or more soil strata. Since macrocells are responsible for many of the instances of severe corrosion of underground structures, one would expect a correlation to exist between soil moisture content and underground corrosion. Such correlations are found in the literature. For example, Booth et al.,[9] found that only resistivity and redox potential were better predictors of corrosivity than moisture content. Soils containing greater than 20 weight percent water were considered to be aggressive while those containing less than 20 weight percent were non-aggressive.

Soil Type

Soil type is also an important factor affecting piling corrosion. This is a broad category that includes soil particle-size distribution, soil stratification, man-made versus natural soils and cation-exchange capacity. The classification of soils is based on particle-size distribution. In the Unified Soil Classification System (USCS), clays are defined as having a grain size of less than 5 μm while silt has a particle size between 5 μm and 75 μm and sand has a particle size between 75 μm and 4.75 mm. Because of their small particle size and chemical properties, clays hold moisture better than silt and sand and tend to be deficient in oxygen. When a pile is driven through a stratified soil containing layers of clay and silt or sand, the clay strata become the anodes in the differential aeration cells and the silt or sand become the cathodes. All of the severe cases of piling corrosion have been observed in stratified soils.

Man-made products such as slag and cinders also were present in the majority of severe cases of piling corrosion. In those cases, the soils were stratified, with layers of man-made products and clays. The man-made products are corrosive for a number of reasons; they are porous, allowing oxygen access to the pile, have low resistivities, and frequently have a low pH.

Disturbed natural soil is relatively less aggressive than man-made products, but can be porous, allowing oxygen to reach the pile. On the other hand, undisturbed natural soils are relatively non-corrosive, even above the water table, regardless of the properties.[5] Undisturbed soils are non-corrosive for the same reasons that corrosion is negligible below the water table. Under these conditions. the soils are deficient in oxygen. It should be cautioned that this conclusion should be put in perspective. Few pilings are installed in completely undisturbed soil. Usually, the upper portion of a piling is exposed to some type of fill soil.

Recently, the cation-exchange capacity (CEC) of clays has been shown to affect corrosivity.[10] The CEC is defined as the capacity of a clay to attract cations from solution. This phenomenon occurs as a result of the charge of the clay particles. Long[10] found that the corrosivity of a clay increased with increasing CEC. Clays that have a high CEC, such as montmorillonite (bentonite), were found to be more corrosive both with respect to general corrosion and differential aeration cell corrosion. This relationship between CEC and corrosivity of a clay is not unreasonable in that the ability of a clay to hold moisture and corrosive ions increases with increasing CEC.

Soil Resistivity

Soil resistivity is generally considered to be a significant factor in underground corrosion of steels. Romanoff[11] reported that, in one study, 57% of a pipeline in 1000 ohm-cm soil required repair while the repair was limited to about 3% of the pipeline in 11 500 ohm-cm soil. Typical guidelines for soil corrosivity, taken from a text for the Appalachian Underground Short Course[12] are given below:

0 to 1000 ohm–cm	Very Corrosive
1000 to 2000 ohm–cm	Corrosive
2000 to 10 000 ohm–cm	Mildly Corrosive
above 10 000 ohm–cm	Progressively Less Corrosive

Long[3] investigated the macrocell corrosion of steel pilings and concluded that where severe corrosion occurred, contiguous layers of soil had resistivities below 1000 ohm-cm.

Soil resistivity affects corrosion in several ways. Low resistivity soils generally contain high concentrations of soluble salts. The anions in the salts attack protective oxide films on the steels, accelerating the rate of the electrochemical reactions at the metal surface. Ionic current flow in the soil must occur for macrocells to develop. Where the soil resistivity is low, the magnitude of this current and the spacial separation of the anodes and cathodes can be larger. Thus, macrocell corrosion rates can be higher and a larger area of the pile can be affected.

Soil pH

Like resistivity, soil pH is considered to be one of the primary controlling factors in underground corrosion. In low-pH environments, the protective corrosion product films on steel are destabilized, resulting in localized corrosion or accelerated general corrosion. Where the pH is below about 4, rates of hydrogen ion reduction are sufficiently high to increase rates of corrosion. On the other hand, steel develops protective passive films in alkaline environments. As is the case with soil resistivity, there is a lot of scatter in corrosion rate data and all of the known factors must be considered. For example, Table D-1 shows that high rates of corrosion of pilings have been observed in pH 9 soils.

A simple analysis was performed to examine the combined effects of pH and resistivity on corrosion of piles in soil above the water table. Data were obtained from Table D-1 and Romanoff.[11] Included in the analyses were cases where negligible corrosion was observed. Corrosion rate was plotted as a function of the product of the pH and the log of the soil resistivity. Results are summarized in Figure D-2. These data show a trend of decreasing corrosion rate with increasing value of this product but the scatter in the data is large, as indicated by the low R^2 value for the fitted curve.

The California State DOT has performed a similar analysis for culverts. In California Test 643,[13] a nomogram is provided for estimating the life from resistivity and pH measurements.

Years to Perforation in Years

$$\text{(for 52 mil thick culvert)} = 13.79\,[\log_{10}R - \log_{10}(2160 - 2490\,\log_{10}pH)] \tag{6}$$

A linear corrosion rate is assumed for extrapolation to thicker culverts. The calculated rate from this equation is about a factor of two higher than that estimated from the linear regression shown in Figure D-2, assuming that the culvert calculation represents a one- sided corrosion rate. For example, for a pH 7 soil having a resistivity of 1000 ohm-cm, the culvert equation predicts a time to perforation of 17.3 years for a 52 mil thick culvert. The linear regression shown in Figure D-2 predicts a perforation in forty-seven years. However, if one takes the upper bound of the data shown in Figure D-2, the life estimates are much closer.

Soluble Salts

Very little direct data have been obtained on the effect of soluble salts on corrosion of steel pilings in soils. On the other hand, it is generally recognized that soluble salts are detrimental. These salts decrease the resistivity of the soil and directly affect the electrochemical reactions at the metal surface. Chlorides promote the breakdown of the protective corrosion product films on the metal surface while sulfates can encourage the activity of sulfate-reducing bacteria, which can lead to microbial-influenced corrosion (MIC).

Data showing the effect of salt content on the resistivity of single salt solutions are shown in Figure D-3.[14] These data show a systematic trend of decreasing resistivity with increasing concentration for the calcium sulfate (as sulfate, SO_4) and sodium chloride (as chloride, CL) solutions. A similar behavior would

$$f(x) = -1.189783E-1^*x + 3.614570E+0$$
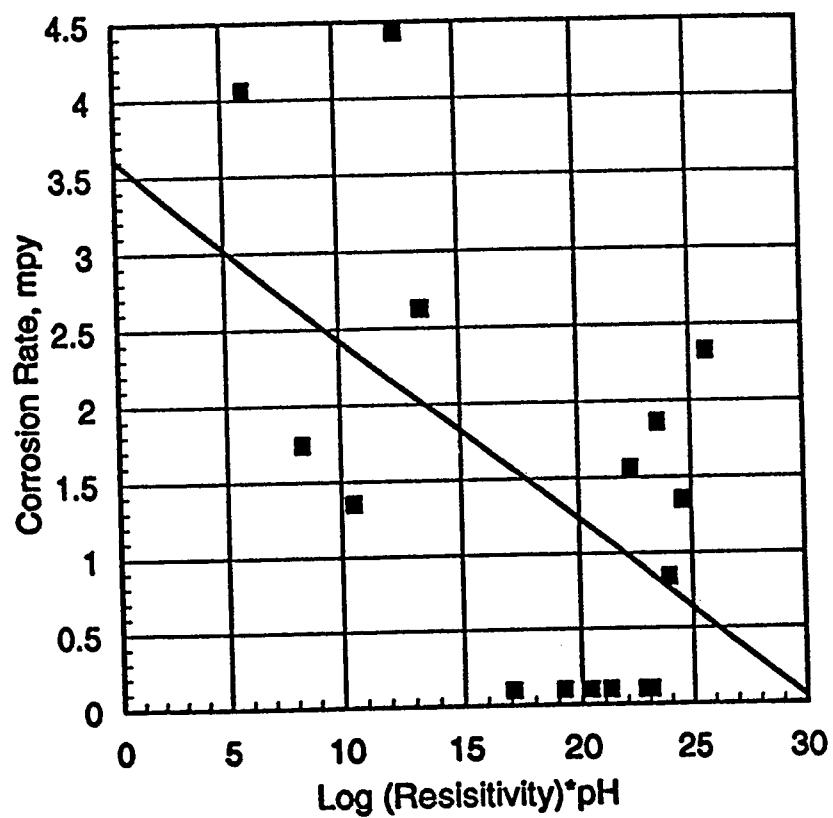$$R^2 = 2.867207E-1$$

Figure D-2. Corrosion Rate as a Function of the Product of pH Times Log Resistivity for Locations on Piles Above Water Table. Data Were Taken from References Shown in Table 2.[1-5]
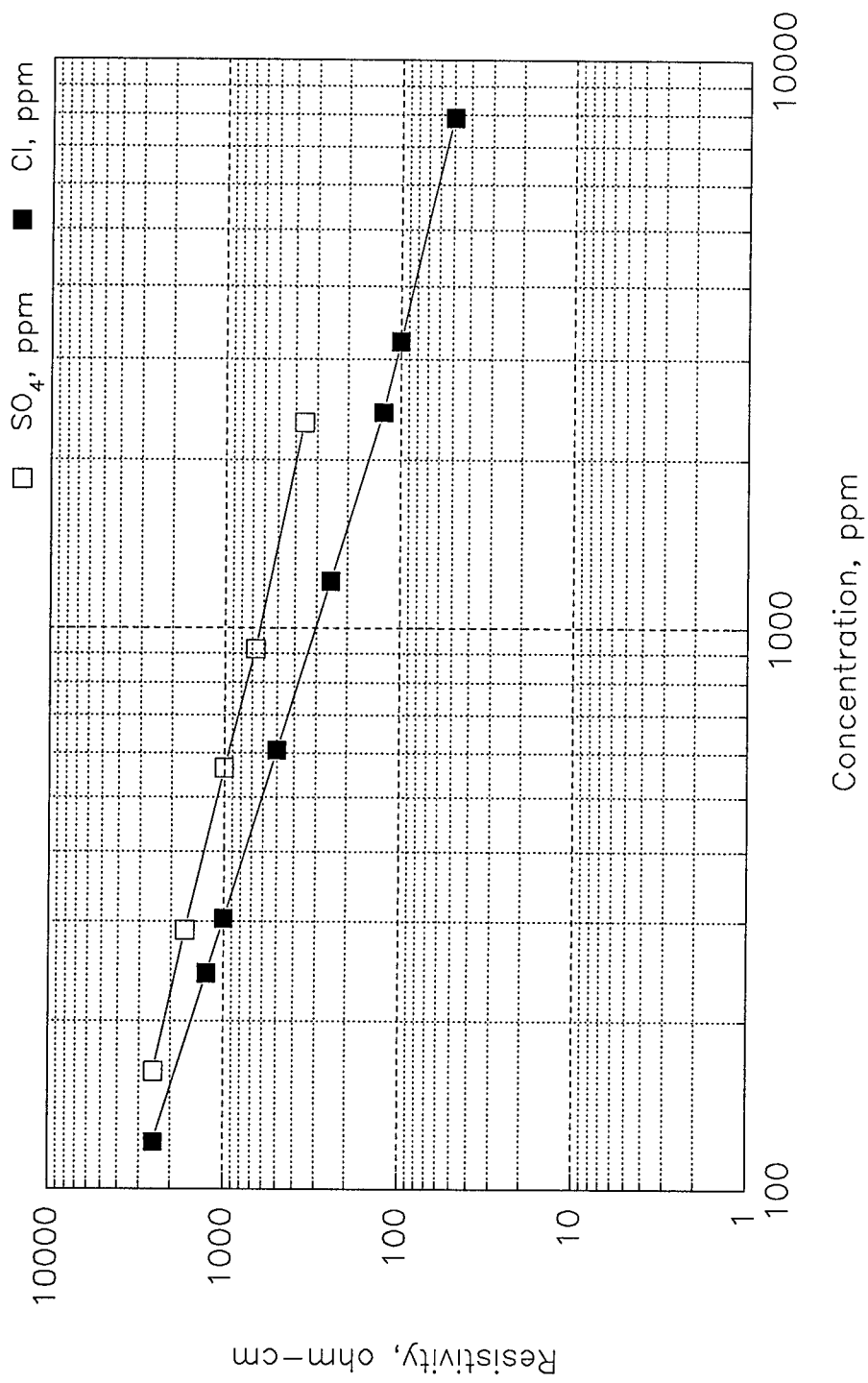
Figure D-3.   Resistivity as a Function of Concentration for CaSO$_4$ and NaCl Solutions at Room Temperature.[14]

be expected for more complex salt solutions. Romanoff[11] reported on one study of the effect of chemical composition of soils, including soluble salts, on the corrosion behavior of an underground pipeline. It was found that soil resistivity measurements, made at the same time on the pipeline, were as reliable as the more detailed chemical analysis in identifying corrosive soils.

Potential and Eh

Correlations have been established between corrosivity of soils and two types of potential measurements; the free-corrosion potential of the underground steel structure and the soil redox potential (Eh). The free-corrosion potential of steel is measured by placing a copper–copper sulfate (CCS) reference electrode in the ground over the structure and measuring the voltage difference between the steel and the reference electrode using a high impedance voltmeter. Where the soil is stratified, the potential measured will be some average value. More accurate measurements of the potential of the steel within each stratum can be obtained by boring down to the stratum and placing a reference electrode close to the structure. The corrosion potential of a metal is established by the corrosion kinetics, it represents the potential at which the sum of the oxidation reactions (metal corrosion and any other non-corrosion oxidation reactions on the metal surface) equals the sum of the reduction reactions (oxygen reduction + water reduction, etc.).

The Eh is measured in a similar fashion, but the potential of a platinum electrode, instead of the steel structure, is measured. For the Eh measurement, the platinum electrode is placed in the soil stratum of interest whereas the reference electrode can be placed on the ground surface. The Eh is a measure of the oxidizing or reducing strength of the soil. Where the soil is oxidizing (aerobic) the value is more positive than where the soil is reducing (anaerobic). In unsaturated soil, aerobic conditions prevail and the Eh values tend to be more positive.

Table D-2 provides guidelines for soil corrosivity based on either steel potential or Eh measurements. The table shows that steel in the most corrosive soils has more negative potentials based on either type of potential measurement. It should be cautioned that these guidelines are based on years of experience with pipelines and other underground structures that typically are above or at the water table. A negative value for the Eh or corrosion potential indicates that reducing sites are present and that the likelihood of corrosion by a differential

Table D-2. Corrosivity as a Function of Eh of Soil[11] or Corrosion Potential of Steel in Soil.[15]

CORROSIVITY	Eh mV (SHE)	CORROSION POTENTIAL mV (CCS)
Non-corrosive	>400	>-400
Slight	200 to 400	-400 to -500
Moderate	100 to 200	-500 to -600
Severe	<100	<-600

aeration cell is high. In this context, these data are consistent with recent data obtained for piles. For example, Long[10] found an excellent correlation between galvanic current and the potential of the clay layer, as shown in Figure D-4.

On the other hand, the guidelines in Table D-2 should not be applied to piles that are completely beneath the water table. Under these conditions one would expect negative potential and Eh values yet negligible corrosion.
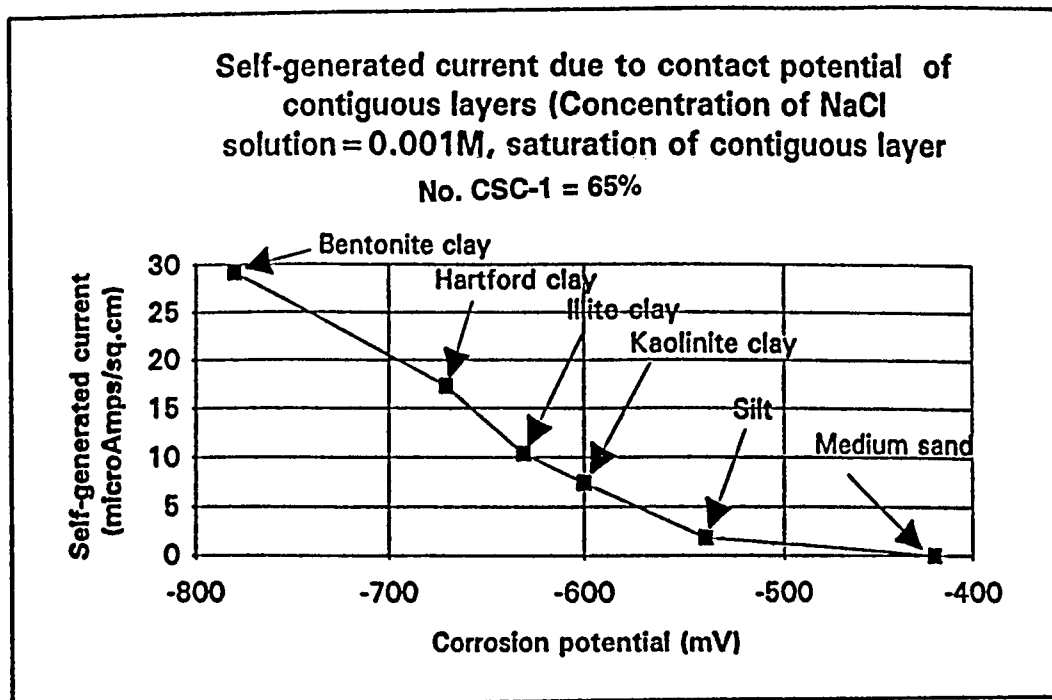
Figure D-4. Galvanic Current as a Function of Corrosion Potential of Steel in Clay for Macrocell Tests Performed with Sand/Clay Layers in 0.001 M NaCl Solution.[10]

Microbes

The damaging effect of microbial influenced corrosion (MIC) on underground structures such as pipelines is well established.[16] Microbes do not directly attack a metal; they promote corrosion by generating corrosive environments. Although the effect of aerobic, acid-producing, and general anaerobic bacteria are not well-documented in the literature, sulfate-reducing bacteria (SRB's) are commonly associated with accelerated corrosion of underground pipelines. The corrosive environment generated by SRB's is reducing and contains high levels of sulfides. These conditions can exacerbate the development of differential aeration cells. On the other hand, several studies[17-19] have reported high levels of sulfate-reducing bacteria (SRB) on the surfaces of piles and yet the extent of corrosion was negligible. The regions of the piles analyzed for SRB's were well below the water table suggesting that MIC, like other forms of corrosion, is not a problem for piles at locations well below the water table. However, MIC should be considered as a possible contributor to corrosion of piling at or above the water table.

Stray Current Corrosion

Piling and other underground structures can undergo accelerated corrosion as a result of stray current flow in the soil.[11] This form of corrosion is referred to as stray current corrosion or stray current electrolysis. Sources of stray current include cathodic protection systems for other structures, direct current (DC) electric transit systems, mining activity, and high voltage DC electric power lines. DC electric current, flowing parallel to a structure, will jump onto that structure if that structure has a lower resistance in the direction of the current flow than the soil. The structure is cathodically protected where the current jumps onto the structure and corrosion is accelerated where the current leaves the structure. Stray current corrosion is most commonly observed on structures that have large dimensions in one horizontal direction, such as pipelines. Sheet piling and other piling that are electrically continuous also can experience stray current corrosion.

REFERENCES

1. Lamb, S. E., "I-990 Ramps Over Sweet Home Road: Replacement of West Abutments with Reinforced Earth," Soil Mechanics Bureau, New York State Department of Transportation, PIN 5126.24, February 1989.

2. Lamb, S. E. and O. E. Picozzi, "Reconstruction of Route 5 Father Baker Bridge, Cities of Buffalo & Lackawana, Erie County," New York State Department of Transportation, Soil Mechanics Bureau & Materials Bureau, PIN 5034.43, D500769, February 1990.

3. Long, R. P. and F. C. Huang, "Corrosion of Driven Steel Piles," Final Report, JHR 90-193, Department of Civil Engineering, University of Connecticut, Storrs, CT, Connecticut Department of Transportation, May 1990.

4. Greene, N. D., R. P. Long, J. Badinter, and P. R. Kambala, "Corrosion of Steel Piles," Corrosion '95, Paper No. 17, National Association of Corrosion Engineers, 1995.

5. Romanoff, M., "Corrosion of Steel Pilings in Soils," National Bureau of Standards Monograph 58, October 1962.

6. Picozzi, O. E., S. E. Lamb, and A. C. Frank, "Evaluation of Prediction Methods for Pile Corrosion at the Buffalo Skyway," New York State Department of Transportation, Technical Services Division, February 1993.

7. Anon., "Report on Corrosion of Underground Steel Piling," Office of the Chief of Engineers, Engineering Study ES-311, Lower Mississippi Valley Division, Corps of Engineers, Vicksburg, MS, December 1969.

8. Thompson, N. G. and G. H. Koch, "Effects of Seasonal Variation on Requirements to Prevent Corrosion in Soils," A.G.A., Arlington, VA, 1986.

9. Booth, G. H., A. W. Cooper, and P. M. Cooper, "Criteria of Soil Aggressiveness Towards Buried Metals. II. Assessment of Various Soils," British Corrosion Journal, Vol. 2, May 1967, p. 109.

10. Long, R. P., J. Badinter, and P. R. Kambala, "Investigation of Steel Pile Foundations in Corrosively Active Areas," Report Number JHR 95-239, Department of Civil Engineering, University of Connecticut, Storrs, CT, Connecticut Department of Transportation, March 1995.

11. Romanoff, M., "Underground Corrosion," National Bureau of Standards Circular 579, 1957, Reprinted by National Association of Corrosion Engineers, 1989.

12. Anon., "Basic Course, Appalachian Underground Corrosion Short Course," West Virginia University, Morgantown, WV, 1985.

13. Anon., "Method for Estimating the Service Life of Steel Culverts," State of California Department of Transportation, Division of New Technology and Materials Research, California Test 643, 1993.

14. Anon., USDA Handbook No. 60, L. A. Richard, Editor, U. S. Department of Agriculture, Washington, D.C., 1969.

15. Lee, R. U. and A. H. Clark, "Corrosion of Steel Pilings in Soil," Corrosion '93, Paper No. 6., National Association of Corrosion Engineers, 1993.

16. Pope, D. H., et al., "Mitigation Strategies for Microbial Influenced Corrosion in Gas Industry Facilities," Corrosion '89, Paper 192, National Association of Corrosion Engineers, 1992.

17. Morley, J., "A Review of the Underground Corrosion of Steel Piling," Steel Construction, Vol. 13, No. 4, July 1989, pp. 13-18.

18. Eadie, G. R., "Corrosion of Steel Piling – Results from a Test at Burley, Victoria," SEAISI Quarterly, Vol. 7, No. 4, October 1978, pp. 34-40.

19. Beckwith, N. R., "Corrosion Test Program of Steel Pipes in River Murray Swampland, South Australia," Corrosion Australasia, Vol. 6, No. 3, June 1981, pp. 11-16.

Case Histories of Significant Piling Corrosion

Case 2

Location: Sweet Home Road Bridge – Buffalo, NY
Date of Examination: June 1988
Date of Installation: 1981
Age of Pile: 7 years
Steel Type: Carbon Steel
Original Thickness: –
Minimum Thickness: –
Maximum Section Loss: –
Percent Section Loss: Moderate to Heavy Section Loss
One-Side Corrosion Rate: –

Location of Maximum
Corrosion Rate: At Transition Between Cinders and Clay in Poorly Drained Area

Soil Properties at Location
of Maximum Corrosion:
pH: –
Resistivity: –
Chlorides: –
Sulfates: –

Description: In June 1988, the west abutments for the I-990 ramp over Sweet Home Road, Buffalo, New York, were reconstructed. During original construction in 1981-1982, cinders were used as lightweight backfill for the reinforced earth abutments. Severe corrosion of the reinforcing strips in the cinders backfill was observed. The backfill was found to be poorly drained and the severity of corrosion increased with moisture content of the backfill. During the reconstruction, the cinder fill was removed and the pilings were examined. At the transition between the cinder backfill and the in situ clay soil, the H-piles showed moderate to heavy section loss.

Reference: Anon., "I-990 Ramps Over Sweet Home Road: Replacement of West Abutments With Reinforced Earth," State of New York, Department of Transportation, Soil Mechanics Bureau & Materials Bureau, PIN 5216.24, February 1990.

Case 1

Location: Father Baker Bridge – Buffalo, NY
Date of Examination: October 1989
Date of Installation: 1957 (approximate)
Age of Pile: 32 years
Steel Type: A-36 Carbon Steel
Original Thickness: 0.436 inches
Minimum Thickness: 0.297 inches
Maximum Section Loss: 0.139 inches
Percent Section Loss: 32%
One-Side Corrosion Rate: 2.17 mpy

Location of Maximum
Corrosion Rate: At or Near Water Table in Dark Green Slag

Soil Properties at Location
of Maximum Corrosion:
pH: 9.0-9.3
Resistivity: 733-1133 ohm-cm
Chlorides: 223-267 ppm
Sulfates: 115-176 ppm

Description: In October, 1989, nine piles from the abutments on the Father Baker Bridge were removed and examined during a reconstruction project. The bridge was located on Route 5 south of Buffalo, NY in Erie County. The piles were initially driven through miscellaneous fill including locally produced industrial waste, containing cinders and slag. Soil samples were obtained from test pits dug adjacent to the piles and analyzed.

Severe corrosion occurred on some piles with the most significant attack in the vicinity of the water table. Other piles experienced much less attack in spite of the fact that the results of the analyses of the soils were similar. It was concluded that there was not a good correlation between the results of the analyses performed (pH, resistivity, chlorides, and sulfates) and the extent of corrosion attack.

Reference: S. E. Lamb and O. E. Picozzi, "Reconstruction of Route 5 Father Baker Bridge, Cities of Buffalo & Lackawana, Erie County," State of New York, Department of Transportation, Soil Mechanics Bureau & Materials Bureau, PIN 5034.43, D500769, February 1990.

Case 4

Location: Sparrows Point, MD
Date of Examination: November 1960
Date of Installation: 1942
Age of Pile: 18 years
Steel Type: Carbon Steel
Original Thickness: 0.550 inches
Minimum Thickness: 0.390 inches
Maximum Section Loss: 0.160 inches
Percent Section Loss: 29%
One-Side Corrosion Rate: 4.43 mpy

Location of Maximum
Corrosion Rate: Near Water Table in Slag/Cinder/Fine Sand

Soil Properties at Location
of Maximum Corrosion:

pH: 3.7
Resistivity: 1130-4000 ohm-cm
Chlorides: –
Sulfates: –

Description: In 1942, several 14 inch × 140 feet H-piles were driven at the Sparrows Point Plant of Bethlehem Steel Company. Two piles were extracted in November 1960. The area was originally a shallow water marsh which was filled with slag and cinders. The pattern and extent of corrosion was similar for the two piles. Significant corrosion was confined to two areas; in the cinders/slag in the water table zone and at a depth of about 115 feet where the piling passed through a sand and gravel bed. Near the water table, average reductions in cross section were 14 to 29%. In the deep sand/gravel zone, reductions in cross section were 4 to 9%.

Reference: M. Romanoff, "Corrosion of Steel Pilings in Soils," National Bureau of Standards Monograph 58, October 1962.

Case 3

Location: I-84 / I-91 Interchange, Hartford, CN
Date of Examination: October 1988
Date of Installation: 1959
Age of Pile: 29 years
Steel Type: Carbon Steel
Original Thickness: 0.375 inches
Minimum Thickness: 0.131 inches
Maximum Section Loss: 0.244 inches
Percent Section Loss: 65%
One-Side Corrosion Rate: 4.21 mpy

Location of Maximum
Corrosion Rate: Above water table in clay with coal/ashes

Soil Properties at Location
of Maximum Corrosion:

pH: 3.8
Resistivity: 380 ohm-cm
Chlorides: –
Sulfates: –

Description: In 1988, a renovation and enlargement was begun on the I-84 / I-91 interchange in Hartford, CN. The excavation process uncovered the upper portions of most of the original piles. At least thirty piles exhibited losses in cross section of greater than 30% and losses were as high as 65%. The corrosion occurred in a narrow (<1 meter) zone, 1.5 to 5 meters below the surface. Above and below this zone, attack was negligible. The soil around the attacked piles consisted of layers of natural and man-made materials. The most severe attack occurred in a thin layer of clay containing coal and ashes.

References: R. H Long and F. C. Huang, "Corrosion of Driven Steel Piles," Civil Engineering Department, School of Engineering, University of Connecticut, Storrs, Connecticut, JHR 90-193, May 1990.

N. D. Greene, R. P. Long, J. Badinter, and P. R. Kambala, "Corrosion of Steel Piles," Corrosion/95, Paper No. 17.

Case 6

Location: Sardis Dam Outlet, Sardis, MS
Date of Examination: October 1959
Date of Installation: 1939
Age of Pile: 20.5 years
Steel Type: Carbon Steel
Original Thickness: 0.375 inches
Minimum Thickness: 0.304 inches
Maximum Section Loss: 0.071 inches
Percent Section Loss: 19%
One-Side Corrosion Rate: 1.73 mpy

Location of Maximum
Corrosion Rate *: In Fill/Riprap about 5 Feet Below Water Table

Soil Properties at Location
of Maximum Corrosion:
   pH: 3.0
   Resistivity: 610 ohm-cm
   Chlorides: –
   Sulfates: –

Description: In October 1959, a 19 5/8" wide × 3/8" thick arch-type pile was pulled from the Sardis Dam Outlet channel on the Little Tallahatchie River near Sardis, Mississippi. The upper soil layer consisted of four feet of riprap fill, followed by one foot of gravel, and layered lignite clay and sand below the gravel. The water table was above the ground surface elevation. The most severe attack (19% section loss) was observed in the gravel bed, five feet below the surface.

Reference: M. Romanoff, "Corrosion of Steel Pilings in Soils," National Bureau of Standards Monograph 58, October 1962.

Case 5

Location: Lumber River, Boardman, NC
Date of Examination: December 1958
Date of Installation: 1921
Age of Pile: 37 years
Steel Type: Carbon Steel
Original Thickness: 0.26 inches
Minimum Thickness: 0.156 inches
Maximum Section Loss: 0.104 inches
Percent Section Loss: 40%
One-Side Corrosion Rate: 1.41 mpy

Location of Maximum
Corrosion Rate *: Near Water Table in Gray Fine Sandy Loam

Soil Properties at Location
of Maximum Corrosion:
   pH: 3.4
   Resistivity: 1240 ohm-cm
   Chlorides: –
   Sulfates: –

Description: In 1958, 120 piles were removed from a bridge support over the Lumber River near Boardman, NC. The piles formed a rectangular cofferdam for the bridge support structure. The structure was removed in connection with road improvements. The piles were interlocking I beams, 8 inch × 20 feet with a wall thickness of 0.25 inches. Approximately 2.5 feet of each pile was above ground and exposed to partial or total immersion about 50% of the year. The highest corrosion rates were in the above ground portions of the piles, with wall losses exceeding 76% (one-side corrosion rate of 2.56 mpy). In the below ground portion of the pile, the highest corrosion rate occurred directly below the soil line, in a gray, fine, sandy loam.

Reference: M. Romanoff, "Corrosion of Steel Pilings in Soils," National Bureau of Standards Monograph 58, October 1962.

* For the below-ground portion of the pile. As described above, the highest corrosion rate was found in the above-ground portion of the pile which was exposed to seasonal water fluctuations.

Case 7

Location:	Grenada Dam spillway, Grenada, MS
Date of Examination:	March 1960
Date of Installation:	October 1948
Age of Pile:	11.4 years
Steel Type:	Carbon Steel
Original Thickness:	0.375 inches
Minimum Thickness:	0.304 inches
Maximum Section Loss:	0.071 inches
Percent Section Loss:	19%
One-Side Corrosion Rate:	3.11 mpy
Location of Maximum Corrosion Rate[*]*:*	Above Water Table in Red Silty Sand with pieces of gray shale.
Soil Properties at Location of Maximum Corrosion:	pH: 6.4
	Resistivity: 4000 ohm-cm
	Chlorides: –
	Sulfates: –

Description: In March 1960, 15" wide × 3/8" thick arch-type piles from the wing walls of the upstream wingwalls of the Grenada Dam Spillway, on the Yalobusha River, were exposed and examined. About seven feet of the piles were exposed and examined, from three feet below the surface to ten feet below the surface. The water table was greater than ten feet below the surface. The upper soil layer consisted of eight feet of fill soil. This soil was a reddish-brown, fine, sandy loam with clods of clay. The remaining two feet of soil exposed consisted of a mixture of light rust-colored, silty sand with pieces of gray shale. The most severe attack (19% section loss) was observed in the lower undisturbed soil layer near the interface with the fill soil.

Reference: M. Romanoff, "Corrosion of Steel Pilings in Soils," National Bureau of Standards Monograph 58, October 1962.

APPENDIX E

Laboratory Soil Cell Data

Table E-1. Analysis of Sand and Bentonite.

Soil	Particle Size Analysis (USCS Classification)			CEC meq/100g	pH ASTM D 4972		Resistivity (Saturated) Ω-cm	Corrosivity	Soluble Chloride mg/kg AASHTO T 291	Soluble Sulfate mg/kg AASHTO T 290	% Moisture AASHTO T 265@60°C
	% Gravel	% Sand	% Fines		DI H$_2$O	CaCl$_2$ H$_2$O					
Sand	0.00	99.62	0.38	0	3.04	3.23	7,300	Mildly Corrosive	27	120	0
Bentonite	0.00	0.00	100.00	76	7.42	7.52	230	Very Corrosive	1,133	197	3.99

Table E-2. Soil Cell Data For Sand and Bentonite.

Soil	Mstr. %	Mstr. Comp.	Polarization Resistance Ω-cm² (mpy)									Coupon Wt. Loss (mpy)	Potential, mV (CCS)								
			9/13/96 1 Day	9/20/96 8 Days	9/26/96 14 Days	10/3/96 21 Days	10/4/96 22 Days	10/10/96 28 Days	10/17/96 35 Days	11/6/96 55 Days	12/6/96 85 Days	12/6/96 85 Days	9/13/96 1 Day	9/20/96 8 Days	9/26/96 14 Days	10/3/96 21 Days	10/4/96 22 Days	10/10/96 28 Days	10/17/96 35 Days	11/6/96 55 Days	12/6/96 85 Days
Sand	12 → 0	Deionized Water	7,418 (1.98)	371,318 (0.04)	470,762 (0.03)	660,514 (0.02)	-	873,211 (0.02)	1,072,794 (0.01)	2,390,220 (0.006)	-	0.71	-660	-522	-491	-475	-	-472	-433	-381	-
Sand	12 → 5.4	10 ppm NaCl	193,731 (0.08)	287,537 (0.05)	330,344 (0.04)	-	400,702 (0.04)	515,465 (0.03)	428,099 (0.03)	283,336 (0.05)	5,083,577 (0.003)	1.14	-666	-545	-513	-	-490	-481	-457	-441	-426
Bentonite	24 → 24	Deionized Water	44,787 (0.44)	60,371 (0.32)	56,403 (0.35)	67,883 (0.29)	-	101,795 (0.20)	106,217 (0.19)	125,944 (0.16)	246,272 (0.08)	0.85	-453	-398	-392	-372	-	-363	-352	-314	-276
Bentonite	24 → 18	10 ppm NaCl	75,196 (0.26)	87,704 (0.23)	74,063 (0.27)	-	105,380 (0.19)	136,250 (0.15)	109,745 (0.18)	305,558 (0.06)	341,752 (0.06)	0.83	-416	-397	-397	-	-359	-356	-334	-269	-116

Table E-3. Soil Cell Data From Soil Sampled at the Buffalo Site.

Soil Sample No.	Mstr. %	Polarization Resistance Ω - cm² (mpy)							Coupon Weight Loss (mpy)	Potential, mV (CCS)						
		9/13/96 1 Day	9/20/96 8 Days	9/26/96 14 Days	10/4/96 22 Days	10/10/96 28 Days	10/17/96 35 Days	11/6/96 55 Days	12/6/96 85 Days	9/13/96 1 Day	9/20/96 8 Days	9/26/96 14 Days	10/4/96 22 Days	10/10/96 28 Days	10/17/96 35 Days	11/6/96 55 Days
6	12 → 5.3	276,081 (0.08)	144,277 (0.015)	89,075 (0.25)	100,856 (0.22)	148,885 (0.15)	90,918 (0.24)	88,542 (0.25)	3.77	-864	-865	-862	-847	-854	-847	-836

Table E-4. Soil Cell Data From Soil Sampled From the CCT Site.

Soil Sample No.	Mstr. %	Polarization Resistance Ω - cm² (mpy)							Coupon Weight Loss (mpy)	Potential, mV (CCS)						
		9/13/96 1 Day	9/20/96 8 Days	9/26/96 14 Days	10/4/96 22 Days	10/10/96 28 Days	10/17/96 35 Days	11/6/96 55 Days	12/6/96 85 Days	9/13/96 1 Day	9/20/96 8 Days	9/26/96 14 Days	10/4/96 22 Days	10/10/96 28 Days	10/17/96 35 Days	11/6/96 55 Days
3	31 → 7	24,735 (0.82)	36,924 (0.55)	30,083 (0.68)	83,963 (0.24)	141,910 (0.14)	220,627 (0.09)	1,173,444 (0.02)	1.95	-812	-807	-812	-797	-783	-749	-560

Table E-5. Laboratory Corrosion Probe Data From Sand/Bentonite Soil.

Soil	Mstr. %	Depth mm	Galvanic Current[1] µA/cm² (mpy)							Polarization Resistance Ω·cm² (mpy)							Wt. Loss (mpy)	Potential, mV (CCS)						
			9/24/96 5 Days	10/4/96 15 Days	10/10/96 21 Days	10/17/96 28 Days	11/14/96 56 Days	12/13/96 85 Days	1/10/97 113 Days	9/24/96 5 Days	10/4/96 15 Days	10/10/96 21 Days	10/17/96 28 Days	11/14/96 56 Days	12/13/96 85 Days	1/10/97 113 Days	1/10/97 113 Days	9/24/96 5 Days	10/4/96 15 Days	10/10/96 21 Days	10/17/96 28 Days	11/14/96 56 Days	12/13/96 85 Days	1/10/97 113 Days
Sand	12	5.57	-	-	-	-	-	-	-	45 (32.8)	194,000 (0.08)	282,182 (0.05)	172,444 (0.08)	91,294 (0.16)	59,124 (0.25)	49,664 (0.30)	0	-418	-527	-475	-503	-415	-529	-522
Sand	12	17.43	28.36 (13.41)	0 (0)	-0.121 (-0.057)	-0.347 (-0.164)	0.739 (0.350)	1.414 (0.699)	0.236 (0.112)	-	-	-	-	-	-	-	0	-	-	-	-	-	-	-
Sand	12	30.83	41.13 (19.44)	0.172 (0.081)	0.366 (0.173)	1.175 (0.555)	2.118 (1.002)	6.248 (2.954)	6.479 (3.063)	-	-	-	-	-	-	-	0	-	-	-	-	-	-	-
Sand	12	43.53	288.83 (136.55)	-0.125 (-0.069)	0.683 (0.323)	5.054 (2.390)	8.170 (3.863)	12.415 (5.870)	13.802 (6.526)	-	-	-	-	-	-	-	0	-	-	-	-	-	-	-
Bentonite	24	56.97	-662.691 (-313.307)	1.503 (0.711)	0.673 (0.318)	-8.153 (-3.854)	5.088 (2.406)	12.033 (5.689)	-6.976 (-3.298)	-	-	-	-	-	-	-	2.431	-	-	-	-	-	-	-
Bentonite	24	68.71	2220.14 (1049.64)	-5.464 (-2.583)	-6.188 (-2.926)	-4.900 (-2.316)	-0.170 (-0.080)	-12.970 (-6.132)	-0.260 (-0.123)	-	-	-	-	-	-	-	7.021	-	-	-	-	-	-	-
Bentonite	24	80.97	2585.56 (1222.40)	4.483 (2.120)	4.470 (2.113)	7.940 (3.754)	-18.689 (-8.836)	-24.121 (-11.404)	-17.140 (-8.104)	-	-	-	-	-	-	-	4.803	-	-	-	-	-	-	-
Bentonite	24	93.67	-	-	-	-	-	-	-	690 (28.8)	17,897 (1.12)	10,924 (1.82)	8,123 (2.44)	3,300 (6.02)	1,780 (11.16)	1,810 (10.97)	2.258	-410	-433	-450	-410	-536	-627	-623

1 Positive values indicate that these rings were cathodic (non-corroding).

Table E-6. Laboratory Corrosion Probe Data From Soil Sampled at the Buffalo Site.

Soil Sample No.	Mstr. %	Depth mm	Galvanic Current[1] µA/cm² (mpy)							Polarization Resistance Ω - cm² (mpy)							Weight Loss (mpy)	Potential, mV (CCS)						
			9/25/96 6 Days	10/4/96 15 Days	10/10/96 21 Days	10/17/96 28 Days	11/14/96 56 Days	12/13/96 85 Days	1/10/97 13 Day	9/25/96 6 Days	10/4/96 15 Days	10/10/96 21 Days	10/17/96 28 Days	11/14/96 56 Days	12/13/96 85 Days	1/10/97 13 Day	1/10/97 113 Days	9/25/96 6 Days	10/4/96 15 Days	10/10/96 21 Days	10/17/96 28 Days	11/4/96 56 Days	12/13/96 85 Days	1/10/97 113 Days
8	12.6	6.46	-	-	-	-	-	-	-	332,500 (0.067)	7,980 (2.78)	5,503 (4.04)	4,092 (5.43)	6,320 (3.52)	7,785 (2.85)	8,992 (2.47)	5.639	-788	-602	-589	-591	-613	-607	-598
8	12.6	17.22	3.864 (1.827)	6.003 (2.838)	12.239 (5.786)	-17.295 (-8.177)	17.161 (8.113)	24.230 (11.455)	17.862 (8.445)	-	-	-	-	-	-	-	1.900	-	-	-	-	-	-	-
8	12.6	30.38	1.467 (0.694)	2.876 (1.360)	-6.298 (-3.276)	14.510 (6.860)	12.950 (6.122)	17.343 (8.199)	12.812 (6.057)	-	-	-	-	-	-	-	1.380	-	-	-	-	-	-	-
8	12.6	43.25	19.716 (9.321)	13.345 (6.309)	30.685 (14.507)	7.941 (3.754)	-3.647 (-1.724)	-8.769 (-4.146)	-7.041 (-3.329)	-	-	-	-	-	-	-	4.915	-	-	-	-	-	-	-
9	32	55.61	-29.117 (-13.766)	-17.638 (-8.339)	-31.245 (-14.772)	-25.852 (-12.222)	-10.096 (-4.773)	-16.034 (-7.581)	-6.858 (-3.242)	-	-	-	-	-	-	-	6.305	-	-	-	-	-	-	-
9	32	68.16	4.255 (2.012)	1.904 (0.900)	-6.763 (-3.198)	-2.616 (-1.237)	-6.522 (-3.084)	-8.796 (-4.159)	-9.386 (-4.438)	-	-	-	-	-	-	-	4.751	-	-	-	-	-	-	-
9	32	81.88	-1.626 (-0.769)	-3.672 (-1.736)	-10.252 (-4.847)	-8.771 (-4.147)	-8.802 (-4.161)	-10.305 (-4.782)	-11.657 (-5.511)	-	-	-	-	-	-	-	5.565	-	-	-	-	-	-	-
9	32	93.72	-	-	-	-	-	-	-	25,3793 (0.088)	1,963 (11.32)	1,863 (11.93)	1,155 (19.24)	3,067 (7.25)	3,505 (6.34)	2,003 (11.09)	2.259	-827	-662	-710	-672	-767	-804	-761

1 Positive values indicate that these rings were cathodic (non-corroding).

Table E-7.   Laboratory Corrosion Probe Data From Soil Sampled at the CCT Site.

Soil Sample No.	Mstr. %	Depth, mm	Galvanic Current[1] µA/cm² (mpy) 9/25/96 5 Days	10/4/96 14 Days	10/10/96 20 Days	10/17/96 27 Days	11/14/96 55 Days	11/27/96 68 Days	12/13/96 84 Days	1/10/97 112 Days	Polarization Resistance Ω-cm² (mpy) 9/25/96 5 Days	10/4/96 14 Days	10/10/96 20 Days	10/17/96 27 Days	11/14/96 55 Days	11/27/96 68 Days	12/13/96 84 Days	1/10/97 112 Days	Wt. Loss (mpy) 1/10/97 112 Days	Potential, mV (CCS) 9/25/96 5 Days	10/4/96 14 Days	10/10/96 20 Days	10/17/96 27 Days	11/14/96 55 Days	11/27/96 68 Days	12/13/96 84 Days	1/10/97 112 Days
3	31	4.45	-	-	-	-	-	-	-	-	5,172 (3.93)	7,943 (2.56)	5,233 (3.88)	4,633 (4.39)	6,178 (3.29)	7,539 (2.70)	7,669 (2.65)	8,554 (2.38)	2.359	-740	-741	-700	-714	-754	-763	-771	-769
3	31	14.73	2.400 (1.135)	1.383 (0.654)	2.735 (1.293)	3.986 (1.885)	1.673 (0.791)	1.145 (0.541)	1.495 (0.707)	0.770 (0.364)	-	-	-	-	-	-	-	-	1.171	-757	-	-	-	-	-	-	-
3	31	25.51	4.180 (1.976)	1.418 (0.671)	3.499 (1.654)	6.976 (3.298)	1.974 (0.933)	1.511 (0.714)	1.259 (0.595)	0.879 (0.415)	-	-	-	-	-	-	-	-	0.991	-762	-	-	-	-	-	-	-
3	31	41.19	-0.538 (-0.254)	-0.481 (-0.228)	-0.401 (-0.190)	-1.485 (-0.702)	-0.552 (-0.261)	0.096 (0.045)	-1.039 (-0.491)	0.842 (0.398)	-	-	-	-	-	-	-	-	1.704	-791	-	-	-	-	-	-	-
3	Sat	45.80	0.209 (0.099)	3.441 (1.627)	2.005 (0.948)	-2.445 (-1.156)	-1.455 (-0.688)	-1.195 (-0.565)	-1.139 (-0.539)	-1.022 (-0.483)	-	-	-	-	-	-	-	-	1.671	-789	-	-	-	-	-	-	-
3	Sat	56.34	-2.739 (-1.295)	-2.793 (-1.320)	-4.149 (-1.961)	-3.491 (-1.651)	-1.243 (-0.588)	-1.141 (-0.539)	-1.128 (-0.533)	-0.943 (-0.446)	-	-	-	-	-	-	-	-	1.765	-803	-	-	-	-	-	-	-
3	Sat	66.30	-2.497 (-1.180)	-2.834 (-1.340)	-3.997 (-1.890)	-3.791 (-1.792)	-1.130 (-0.534)	-0.760 (-0.359)	-0.257 (-0.121)	-1.063 (-0.502)	-	-	-	-	-	-	-	-	2.038	-806	-	-	-	-	-	-	-
3	Sat	76.04	-	-	-	-	-	-	-	-	3,057 (6.65)	6,268 (3.24)	6,190 (3.28)	6,784 (3.00)	8,843 (2.30)	7,115 (2.86)	9,787 (2.08)	1,997 (10.18)	1.106	-808	-807	-809	-800	-820	-826	-832	-801

[1] Positive values indicate that these rings were cathodic (non-corroding).

Table E-8.   Tafel Slopes and Factors Determined from Anodic and Cathodic Potentiodynamic Polarization Curves.

Soil	Soil Sample Nº	Moisture, %	Tafel Slope[1]		Tafel Factor[2]	E_c, mV[3]	
			β_a	β_c		Anodic Curve	Cathodic Curve
Sand	-	12	0.156	0.128	0.031	-688	-662
Bentonite	-	24	0.213	0.177	0.042	-463	-463
Buffalo	6	12	0.193	0.251	0.047	-802	-807
CCT	2	30.8	0.157	0.265	0.043	-788	-787
LaGuardia	8	17.6	0.204	0.196	0.043	-606	-619

[1] Literature references indicated that $\beta_a = \beta_c = 0.120$ volts/decade.

[2] Literature references indicated a value of 0.026.

[3] E_c = Corrosion Potential.

Figure E-1.   Photographs of Soil Test Cells Containing Bentonite (Left) and Sand (Right) Used for Polarization Resistance Measurements.

Figure E-2.   Photographs of Soil Test Cells Containing Soil from the Buffalo, New York Field Site (Left) and CC Technologies Field Site (Right) Used for Polarization Resistance Measurements.

Figure E-3. Corrosion Rates Calculated From Polarization Resistance (PR) and Weight-Loss (WL) Measurements for A36 Steel Tested in Various Environments for 85 Days in the Laboratory.

Figure E-4.   Photograph of Laboratory-Sized Corrosion Probe for Galvanic Current Measurements.

Figure E-5.   Corrosion Rates Calculated from Polarization Resistance (PR) and Weight-Loss (WL) Measurements for Laboratory Corrosion Probes Tested in Various Environments for 113 Days in the Laboratory.

Figure E-6.   Galvanic Currents as a Function of Depth and Time, for Coupled Laboratory Corrosion Probe Rings, in Sand and Bentonite.

Figure E-7.   Galvanic Currents as a Function of Depth and Time, for Coupled Laboratory Corrosion Probe Rings, in Soil Sampled from the Buffalo Site (Soil Samples #8 and #9).

Figure E-8.   Galvanic Currents as a Function of Depth and Time, for Coupled Laboratory Corrosion Probe Rings, in Soil Sampled from the CCT Site (Soil Sample #3).

Figure E-9.   Corrosion Potentials as a Function of Depth and Time, for Laboratory Corrosion Probe Rings, in Sand and Bentonite.

Figure E-10.   Corrosion Potentials as a Function of Depth and Time, for Laboratory Corrosion Probe Rings, in Soil Sampled from the Buffalo Site (Soil Samples #8 and #9).

Figure E-11.   Corrosion Potentials as a Function of Depth and Time, for Laboratory Corrosion Probe Rings, in Soil Sampled from the CCT Site (Soil Sample #3).

Figure E-12.   Potentiodynamic Polarization Curves for Sand Containing 12% Moisture.

Bentonite

Figure E-13.   Potentiodynamic Polarization Curves for Bentonite Containing *24% Moisture*.

Figure E-14.   Potentiodynamic Polarization Curves for Soil Sampled at the Buffalo Site (Sample #6) Containing 12% Moisture.

CCT Soils

E (mV)

I (μA/cm²)

Figure E-15.   Potentiodynamic Polarization Curves for Soil Sampled at the CCT Site (Sample #2) Containing 30.8% Moisture.

LaGuardia Soils

E (mV)

I (μA/cm^2)

Figure E-16.   Potentiodynamic Polarization Curves for Soil Sampled at the LaGuardia Site (Sample #8) Containing 17.6% Moisture.

APPENDIX F

Buffalo, New York Field Site Data

Table F-1. Analyses of Soil Sampled at the Buffalo, New York Site.

Field Sample Number	Sample Identity	Depth, Feet	Depth, Inches	Description	Particle Size Analysis (USCS Classification)			CEC, meq/100 g [2]	ASTM G 51	pH ASTM D 4972		Resistivity, Ω-cm		Corrosivity [3]	Soluble Chloride, [4] mg/kg AASHTO T 291	Soluble Sulfate, [4] mg/kg AASHTO T 290	% Moisture AASHTO T 265 @ 60°C
					% Gravel	% Sand	% Fines			DI H2O	CaCl2 H2O	As-Received	Saturated				
1	BS1	0.0 - 1.5	18	Gravel and Sand.	43.65	48.41	7.94	2.80	7.7	8.24	7.30	12,000	1,120	Corrosive	93	60	9.07
2	BS2T	1.5 - 3.0	23	Top 5' of sample; coarse-grained.	68.82	26.85	4.33	2.89	8.4	8.30	7.49	9,080	1,258	Corrosive	82	65	7.04
3	BS2B	1.5 - 3.0	36	Bottom 13' of sample; finer-grained.	55.47	40.33	4.20	6.56	7.6	8.24	7.91	434	111	Very Corrosive	2163	194	12.74
4	BS3	3.0 - 4.5	54	Mixed fill, cobble, gravel, sand, brick & glass	35.17 [1]	57.99	6.84	3.76	7.8	8.25	7.95	110	420	Very Corrosive	5593	260	10.22
5	BS4	4.5 - 6.0	72	Mixed fill, gravel, cinders, slag & sand	72.20	22.66	5.14	4.51	7.7	8.39	8.00	127	120	Very Corrosive	5065	215	26.87
6	BS5	6.0 - 7.5	90	Mixed fill, gravel, cinders, slag & brick	83.62	14.65	1.73	1.56	Too rocky	8.30	8.20	1,150	348	Very Corrosive	2261	724	12.00
7	BS6	7.5 - 9.0	108	Mixed fill, cobble, gravel, cinders & slag	82.08 [1]	16.12	1.80	1.87	≈ 7.9	8.22	8.12	340	110	Very Corrosive	2612	1380	15.01
8	BS7	9.0 - 10.5	126	(Water table @ 9.2') Mixed fill,glass,gravel,brick,cinders & slag	80.94	17.09	1.97	1.87	≈ 7.9	8.38	8.22	480	270	Very Corrosive	2781	1249	12.64
9	BS9	12.0 - 13.5	162	Mixed fill, cobble, wood, gravel, cinders & sand	73.27 [1]	23.68	3.05	4.28	Too rocky	7.69	7.65	Already saturated	145	Very Corrosive	682	729	32.41
10	BS10T	13.5 - 15.0	167	Top 5' of sample; cinders, gravel and fiberous material	62.69	33.44	3.87	5.31	8.2	7.64	7.60	Already saturated	500	Very Corrosive	585	1080	27.50
11	BS10B	13.5 - 15.0	180	Bottom 13' of sample; cinders, gravel, sand and fines	14.33	70.14	15.53	9.38	9.1	7.87	7.75	592	725	Very Corrosive	543	96	17.02
12	BS11	15.0 - 16.5	198	Sand and fines	1.02	84.11	14.87	6.25	6.7	7.92	7.75	580	653	Very Corrosive	398	96	20.16

[1] Contained one large cobble. The cobble in Sample No. 4 was a brick.

[2] Methylene Blue Methenol

[3] Based on resistivity

[4] Corrected for moisute content soil

Table F-2. Analysis of Groundwater Sample Taken at the Buffalo, New York Site.

Parameter	Value
pH	7.3
Conductivity, µS/cm	6.7
Chloride, mg/L	327
Sulfate, mg/L	91
Bacteria, Bacteria/mL (Days) General Aerobic General Anaerobic Acid-Producing Sulfate-Reducing Iron-Related	 >10,000 (2) 1,000 - 10,000 (4) 100 - 1000 (2) 0 (28) >10,000 (4)

Table F-3.   Soil Cell Data From Soil Sampled at the Buffalo Site.

Soil Sample No.	Mstr. %	Polarization Resistance Ω - cm² (mpy)							Coupon Weight Loss (mpy)	Potential, mV (CCS)						
		9/13/96 1 Day	9/20/96 8 Days	9/26/96 14 Days	10/4/96 22 Days	10/10/96 28 Days	10/17/96 35 Days	11/6/96 55 Days	12/6/96 85 Days	9/13/96 1 Day	9/20/96 8 Days	9/26/96 14 Days	10/4/96 22 Days	10/10/96 28 Days	10/17/96 35 Days	11/6/96 55 Days
6	12 → 5.3	276,081 (0.08)	144,277 (0.015)	89,075 (0.25)	100,856 (0.22)	148,885 (0.15)	90,918 (0.24)	88,542 (0.25)	3.77	-864	-865	-862	-847	-854	-847	-836

Table F-4. Laboratory Corrosion Probe Data From Soil Sampled at the Buffalo Site.

Soil Sample No	Mstr. %	Depth mm	Galvanic Current[1] μA/cm² (mpy)							Polarization Resistance Ω - cm² (mpy)							Weight Loss (mpy)	Potential, mV (CCS)						
			9/25/96 6 Days	10/4/96 15 Days	10/10/96 21 Days	10/17/96 28 Days	11/14/96 56 Days	12/13/96 85 Days	1/10/97 13 Day	9/25/96 6 Days	10/4/96 15 Days	10/10/96 21 Days	10/17/96 28 Days	11/14/96 56 Days	12/13/96 85 Days	1/10/97 13 Day	1/10/97 13 Day	9/25/96 6 Days	10/4/96 15 Days	10/10/96 21 Days	10/17/96 28 Days	11/4/96 56 Days	12/13/96 85 Days	1/10/97 113 Days
8	12.6	6.46	-	-	-	-	-	-	-	332,500 (0.067)	7,980 (2.78)	5,503 (4.04)	4,092 (5.43)	6,320 (3.52)	7,785 (2.85)	8,992 (2.47)	5.639	-788	-602	-589	-591	-613	-607	-598
8	12.6	17.22	3.864 (1.827)	6.003 (2.838)	12.239 (5.786)	-17.295 (-8.177)	17.161 (8.113)	24.230 (11.455)	17.862 (8.445)	-	-	-	-	-	-	-	1.900	-	-	-	-	-	-	-
8	12.6	30.38	1.467 (0.694)	2.876 (1.360)	-6.298 (-3.276)	14.510 (6.860)	12.950 (6.122)	17.343 (8.199)	12.812 (6.057)	-	-	-	-	-	-	-	1.380	-	-	-	-	-	-	-
8	12.6	43.25	19.716 (9.321)	13.345 (6.309)	30.685 (14.507)	7.941 (3.754)	-3.647 (-1.724)	-8.769 (-4.146)	-7.041 (-3.329)	-	-	-	-	-	-	-	4.915	-	-	-	-	-	-	-
9	32	55.61	-29.117 (-13.766)	-17.638 (-8.339)	-31.245 (-14.772)	-25.852 (-12.222)	-10.096 (-4.773)	-16.034 (-7.581)	-6.858 (-3.242)	-	-	-	-	-	-	-	6.305	-	-	-	-	-	-	-
9	32	68.16	4.255 (2.012)	1.904 (0.900)	-6.763 (-3.198)	-2.616 (-1.237)	-6.522 (-3.084)	-8.796 (-4.159)	-9.386 (-4.438)	-	-	-	-	-	-	-	4.751	-	-	-	-	-	-	-
9	32	81.88	-1.626 (-0.769)	-3.672 (-1.736)	-10.252 (-4.847)	-8.771 (-4.147)	-8.802 (-4.161)	-10.305 (-4.782)	-11.657 (-5.511)	-	-	-	-	-	-	-	5.565	-	-	-	-	-	-	-
9	32	93.72	-	-	-	-	-	-	-	25,3793 (0.088)	1,963 (11.32)	1,863 (11.93)	1,155 (19.24)	3,067 (7.25)	3,505 (6.34)	2,003 (11.09)	2.259	-827	-662	-710	-672	-767	-804	-761

[1] Positive values indicate that these rings were cathodic (non-corroding).

Table F-5.   Field Corrosion Probe Data From the Buffalo Site.

Soil Sample No.	Field Probe Rings Depth, Inches	Galvanic Current[1] µA/cm² (mpy)		Polarization Resistance Ω - cm² (mpy)		Weight Loss (mpy)	Potential mV (CCS)		
		10/15/96 1.5 Hours	12/3/96 49 Days	10/15/96 1.25 Hours	12/3/96 49 Days	12/3/96 49 Days	10/15/96 0 Hours	12/3/96 49 Days	12/3/96 49 Days, 1/2 Hour
4	42.25 - 46.25	0.652 (0.308)	-1.984 (-0.938)	-	-	7.69	-480	-682	-685
4	46.50 - 50.50	-0.060 (-0.028)	0.389 (0.184)	-	-	6.97	-492	-673	-674
4	50.75 - 54.75	0.757 (0.358)	0.344 (0.163)	29,450 (0.75)	4,467 (4.97)	6.43	-500	-671	-672
5	55.00 - 59.00	0.157 (0.074)	3.293 (1.557)	-	-	5.97	-500	-659	-658
5	69.25 - 73.25	-0.187 (-0.089)	-1.048 (-0.495)	-	-	7.46	-540	-694	-697
6	73.50 - 77.50	-0.442 (-0.209)	-0.741 (-0.350)	-	-	5.95	-556	-696	-698
6	77.75 - 81.75	-0.300 (-0.142)	-0.195 (-0.092)	50,250 (0.44)	11,552 (1.92)	5.55	-560	-689	-691
6	82.00 - 86.00	-0.659 (-0.312)	-0.606 (-0.287)	-	-	5.32	-556	-690	-692

[1] Positive values indicate that these rings were cathodic (non-corroding).

Figure F-1.   Location of Field Site in Buffalo, New York.

Figure F-2.   Plan View of Field Site; Sampling Performed Near Boring Nº 405 by Pier Nº 3.

Steel H Piles HP 10 x 42
Maximum Load 35 Tons

Figure F-3.   Elevation View of Section A-A Near Pier № 3.

Figure F-4.   Elevation View of Pier № 3 and № 4, North and South.

BORING NO. 405
STA. 11 + 55, 21'Lt.
GR. EL. +5.8

DEPTH IN FT.	BLOWS ON S.P. FOR 6 INCHES (ELEV. - FT.)	BLOWS/FT. ON CASING	SYMBOL	DESCRIPTION
0	4,3,2 (-3.2)	19 54 88 6 12 7 800		loose bl. ASHES, SILT and RUBBLE FILL
10	1,1,2 (-7.6) 1,1,1 (-14.2)	12 6 8 7 6 7 14 18 18 18 20		sf. plastic rd. gy. SILT, sm. clay, tr. Sand
20	RUN#1 100% REC. (-19.2)			seamed, LIMESTONE BEDROCK

Note: 2/15/57 noted along left depth column.

Figure F-5.   Boring Log for Boring Nº 405.

Figure F-6. Graphical Representation of Soil Analysis Data, as a Function of Depth, for the Buffalo, New York Site.

Figure F-7.   Particle Size Distribution, as a Function of Depth, for the Buffalo, New York Site.

Figure F-8.   Corrosion Potentials (Measured with Respect to a Copper/Copper Sulfate Reference Electrode) Immediately After Insertion of the Corrosion Probe, as a Function of Depth, at the Buffalo Site.

Figure F-9.   Corrosion Potentials (Measured with Respect to a Copper/Copper Sulfate Reference Electrode) After 49 Days of Galvanic Coupling of
Corrosion Probe Rings, as a Function of Depth, at the Buffalo Site.

Figure F-10.   Corrosion Potentials (Measured with Respect to a Copper/Copper Sulfate Reference Electrode) After 30 Minutes of Depolarization Following 49 Days of Galvanic Coupling of Corrosion Probe Rings, as a Function of Depth, at the Buffalo Site.

Figure F-11. Corrosion Potentials (Measured with Respect to a Copper/Copper Sulfate Reference Electrode) of Corrosion Probe Rings, as a Function of Depth and Time, for the Buffalo Site.

Figure F-12. Corrosion Potentials (Measured with Respect to a Platinum Electrode) Immediately After Insertion of the Corrosion Probe, as a Function of Depth, at the Buffalo Site.

Buffalo, New York Probe, 12-3-96, 49 Days

Depth, inches: -44, -49, -53, -57, -71, -76, -80, -84

Potential, mV (Pt): -900, -880, -860, -840, -820, -800, -780, -760, -740, -720, -700

Figure F-13.   Corrosion Potentials (Measured with Respect to a Platinum Electrode) After 49 Days of Galvanic Coupling of Corrosion Probe Rings, as a Function of Depth, at the Buffalo Site.

Figure F-14. Corrosion Potentials (Measured with Respect to a Platinum Electrode) After 30 Minutes of Depolarization Following 49 Days of Galvanic Coupling of Corrosion Probe Rings, as a Function of Depth, at the Buffalo Site.

Figure F-15.   Corrosion Potentials (Measured with Respect to a Platinum Electrode) of Corrosion Probe Rings, as a Function of Depth and Time, for the Buffalo Site.

Figure F-16. Comparison of Corrosion Potentials Measured with Respect to Copper/Copper Sulfate (CCS) Reference Electrode with Potentials Measured with Respect to Platinum (Pt) Electrode Immediately After Insertion of the Corrosion Probe, as a Function of Depth, at the Buffalo Site.

Figure F-17. Comparison of Corrosion Potentials Measured with Respect to a Copper/Copper Sulfate (CCS) Reference Electrode with Potentials Measured with Respect to Platinum (Pt) Electrode 49 Days and 49 Days + 0.5 Hours After Insertion of the Corrosion Probe, as a Function of Depth, at the Buffalo Site.

Figure F-18. Galvanic Currents 1.5 Hours After Coupling Corrosion Probe Rings, as a Function of Depth, at the Buffalo Site.

Figure F-19. Galvanic Currents 49 Days After Coupling Corrosion Probe Rings, as a Function of Depth, at the Buffalo Site.

Figure F-20. Galvanic Currents of Coupled Corrosion Probe Rings, as a Function of Depth and Time, for the Buffalo Site.

Figure F-21. Comparison of Corrosion Rates Calculated From Polarization Resistance (PR), Weight-Loss (W. Loss), and Galvanic Current Measurements of Field Corrosion Probe Rings, as a Function of Depth, at the Buffalo Site.

Figure F-22. Comparison of Corrosion Rates Calculated From Laboratory and Field Polarization Resistance (PR), Weight-Loss (WL), and Galvanic Current (GC) Measurements, with Soil Sampled at the Buffalo Site.

APPENDIX G

CC Technologies Field Site Data

Table G-1. Analyses of Soil Sampled at the CCT Site.

Sample Number	Field Sample Identity	Depth, Feet	Depth, Inches	Description	Particle Size Analysis (USCS Classification)			CEC, meq/100 g[2]	pH			Resistivity, Ω-cm		Corrosivity[4]	Soluble Chloride,[5] mg/kg AASHTO T 291	Soluble Sulfate,[5] mg/kg AASHTO T 290	% Moisture AASHTO T 265 @ 60°C
					% Gravel	% Sand	% Fines		ASTM G 51	ASTM D 4972 DI H₂O	CaCl₂H₂O	As-Received	Saturated				
1	CCT1	0.0 - 3.0	36	Sand	17.92	74.96	7.12	9.10	6.5	7.05	6.47	1,900	1,980	Corrosive	15	44	25.65
2	CCT2	3.0 - 6.0	72	Sand	23.15	63.12	13.73	4.88	6.4	7.28	7.12	6,900	2,550	Mildly Corrosive	24	35	11.82
3[1]	CCT3T	6.0 - 9.0	108	(Top) Water Table @ ≈ 6 feet. Sand	11.91	77.53	10.56	5.53	6.4	7.53	7.30	(-)[3]	2,220	Mildly Corrosive	6	56	30.81
4[1]	CCT3B	6.0 - 9.0	108	(Bottom) Sand	-	-	-	-	N.D.	N.D.	N.D.	4,800	N.D.	Mildly Corrosive	N.D.[6]	N.D.[6]	16.29

[1] Only resistivity and % moisture measured on samples taken from the top and bottom of CCT3.

[2] Methylene Blue Method

[3] Top portion of soil already saturated. Bottom portion appeared drier, so resistivity performed only on as-received sample.

[4] Based on resistivity

[5] Corrected for moisture content of soil.

[6] N.D. = Not Determined

Table G-2.   Analysis of Groundwater Taken at the CC Technologies Site.

Parameter	Value
pH	6.8
Conductivity, µS/cm	1.4
Chloride, mg/L	12
Sulfate, mg/L	62

Bacteria, Bacteria/mL (Days)
   General Aerobic
   General Anaerobic
   Acid-Producing
   Sulfate-Reducing
   Iron-Related
	
	>10,000 (2)
	1,000 - 10,000 (2)
	100 - 1000 (2)
	1 - 10 (13)
	>10,000 (2)

Table G-3.   Soil Cell Data From Soil Sampled From the CCT Site.

Soil Sample No.	Mstr. %	Polarization Resistance Ω - cm² (mpy)							Coupon Wgt. - Loss (mpy)	Potential, mV (CCS)						
		9/13/96 1 Day	9/20/96 8 Days	9/26/96 14 Days	10/4/96 22 Days	10/10/96 28 Days	10/17/96 35 Days	11/6/96 55 Days	12/6/96 85 Days	9/13/96 1 Day	9/20/96 8 Days	9/26/96 14 Days	10/4/96 22 Days	10/10/96 28 Days	10/17/96 35 Days	11/6/96 55 Days
3	31 → 7	24,735 (0.82)	36,924 (0.55)	30,083 (0.68)	83,963 (0.24)	141,910 (0.14)	220,627 (0.09)	1,173,444 (0.02)	1.95	-812	-807	-812	-797	-783	-749	-560

Table G-4.   Laboratory Corrosion Probe Data From Soil Sampled at the CCT Site.

Soil Sample No.	Mstr. %	Depth %	Depth mm	Galvanic Current[1] μA/cm² (mpy) 9/25/96 5 Days	10/4/96 14 Days	10/10/96 20 Days	10/17/96 27 Days	11/14/96 55 Days	11/27/96 68 Days	12/13/96 84 Days	1/10/97 112 Days	Polarization Resistance Ω-cm² (mpy) 9/25/96 5 Days	10/4/96 14 Days	10/10/96 20 Days	10/17/96 27 Days	11/14/96 55 Days	11/27/96 68 Days	12/13/96 84 Days	1/10/97 112 Days	Wt. Loss (mpy) 1/10/97 112 Days	Potential, mV (CCS) 9/25/96 5 Days	10/4/96 14 Days	10/10/96 20 Days	10/17/96 27 Days	11/14/96 55 Days	11/27/96 68 Days	12/13/96 84 Days	1/10/97 112 Days
3	31	4.45		-	-	-	-	-	-	-	-	5,172 (3.93)	7,943 (2.56)	5,233 (3.88)	4,633 (4.39)	6,178 (3.29)	7,539 (2.70)	7,669 (2.65)	8,554 (2.38)	2.359	-740	-741	-700	-714	-754	-763	-771	-769
3	31	14.73		2.400 (1.135)	1.383 (0.654)	2.735 (1.293)	3.986 (1.885)	1.673 (0.791)	1.145 (0.541)	1.495 (0.707)	0.770 (0.364)	-	-	-	-	-	-	-	-	1.171	-757	-	-	-	-	-	-	-
3	31	25.51		4.180 (1.976)	1.418 (0.671)	3.499 (1.654)	6.976 (3.298)	1.974 (0.933)	1.511 (0.714)	1.259 (0.595)	0.879 (0.416)	-	-	-	-	-	-	-	-	0.991	-762	-	-	-	-	-	-	-
3	31	41.19		-0.538 (-0.254)	-0.481 (-0.228)	-0.401 (-0.190)	-1.485 (-0.702)	-0.552 (-0.261)	0.096 (0.045)	-1.039 (-0.491)	0.842 (0.398)	-	-	-	-	-	-	-	-	1.704	-791	-	-	-	-	-	-	-
3	Sat	45.80		0.209 (0.099)	3.441 (1.627)	2.005 (0.948)	-2.445 (-1.156)	-1.455 (-0.688)	-1.195 (-0.565)	-1.139 (-0.539)	-1.022 (-0.483)	-	-	-	-	-	-	-	-	1.671	-789	-	-	-	-	-	-	-
3	Sat	56.34		-2.739 (-1.295)	-2.793 (-1.320)	-4.149 (-1.961)	-3.491 (-1.651)	-1.243 (-0.588)	-1.141 (-0.539)	-1.128 (-0.533)	-0.943 (-0.446)	-	-	-	-	-	-	-	-	1.765	-803	-	-	-	-	-	-	-
3	Sat	66.30		-2.497 (-1.180)	-2.834 (-1.340)	-3.997 (-1.890)	-3.791 (-1.792)	-1.130 (-0.534)	-0.760 (-0.359)	-0.257 (-0.121)	-1.063 (-0.502)	-	-	-	-	-	-	-	-	2.038	-806	-	-	-	-	-	-	-
3	Sat	76.04		-	-	-	-	-	-	-	-	3,057 (6.65)	6,268 (3.24)	6,190 (3.28)	6,784 (3.00)	8,843 (2.30)	7,115 (2.86)	9,787 (2.08)	1,997 (10.18)	1.106	-808	-807	-809	-800	-820	-826	-832	-801

[1] Positive values indicate that these rings were cathodic (non-corroding).

Table G-5.   Field Corrosion Probe Data From CCT Site.

Soil Sample No	Field Probe Rings Depth, Inches	Galvanic Current[1] µA/cm² (mpy)					Polarization Resistance Ω - cm² (mpy)			Wt. Loss (mpy)	Potential, mV (CCS)					
		10/3/96 24 Hours	10/30/96 26 Days	11/27/96 56 Days	1/2/97 92 Days	1/30/97 120 Days	10/3/96 4 Hour	1/2/97 92 Day	1/30/97 20 Day	1/30/97 120 Days	10/2/96 3 Hour	10/3/96 24 Hours	1/2/97 92 Day	1/30/97 20 Day	1/30/97 120 Days, 1 Hour
2	44.50 - 48.50	0.493 (0.233)	0.196 (0.093)	0.142 (0.067)	0.108 (0.051)	0.087 (0.041)	--	--	--	0.350	-203	-132	-114	-118	-118
2	48.75 - 52.75	0.058 (0.027)	-0.008 (-0.004)	0.007 (0.004)	0.010 (0.005)	0.007 (0.008)	--	--	--	0.280	-212	-135	-117	-120	-121
2	53.00 - 57.00	-0.056 (-0.026)	0.064 (0.030)	0.022 (0.011)	0.010 (0.005)	0.006 (0.003)	8,204 (2.48)	32,816 (0.62)	34,359 (0.59)	0.257	-201	-137	-118	-120	-121
2	57.25 - 61.25	-0.131 (-0.062)	0.086 (0.041)	0.016 (0.008)	0.005 (0.002)	0.004 (0.002)	--	--	--	0.187	-212	-139	-118	-121	-121
2	70.75 - 74.75	-0.127 (-0.060)	-0.091 (-0.043)	-0.045 (-0.021)	-0.034 (-0.016)	-0.026 (-0.012)	--	--	--	0.315	-213	-140	-120	-122	-123
3	75.00 - 79.00	-0.012 (-0.006)	-0.084 (-0.040)	-0.054 (-0.026)	-0.045 (-0.021)	-0.041 (-0.019)	--	--	--	0.268	-210	-139	-121	-123	-124
3	79.25 - 83.25	-0.167 (-0.079)	-0.074 (-0.035)	-0.039 (-0.018)	-0.034 (-0.016)	-0.026 (-0.012)	12,864 (1.58)	27,916 (0.73)	38,953 (0.52)	0.304	-216	-141	-120	-123	-123
3	83.50 - 87.50	-0.139 (-0.066)	-0.101 (-0.048)	-0.054 (-0.026)	-0.041 (-0.019)	-0.032 (-0.015)	--	--	--	0.210	-212	-141	-120	-123	-123

[1] Positive values indicate that these rings were cathodic (non-corroding).

Figure G-1.   Schematic of Subsurface Soil Probe.

Figure G-2.   Graphical Representation of Soil Analysis Data as a Function of Depth for the CCT Site.

Figure G-3.   Particle Size Analysis as a Function of Depth for the CCT Site.

Figure G-4.   Corrosion Potentials (Measured with Respect to a Copper/Copper Sulfate Reference Electrode) 3 Hours After Insertion of the Corrosion Probe, as a Function of Depth, at the CCT Site.

Figure G-5.   Corrosion Potentials (Measured with Respect to a Copper/Copper Sulfate Reference Electrode) 24 Hours After Insertion of the Corrosion Probe, as a Function of Depth, at the CCT Site.

CC Technologies Probe, 1/2/97, 92 Days

Depth, inches: -47, -51, -55, -59, -73, -77, -81, -86

Potential, mV (CCS): -300, -280, -260, -240, -220, -200, -180, -160, -140, -120, -100

Figure G-6.   Corrosion Potentials (Measured with Respect to a Copper/Copper Sulfate Reference Electrode) After 92 Days of Galvanic Coupling of Corrosion Probe Rings, as a Function of Depth, at the CCT Site.

CC Technologies Probe, 1/2/97, 92 Days
(0.75 Hours Later)

Depth, inches

-47
-51
-55
-59
-73
-77
-81
-86

-300 -280 -260 -240 -220 -200 -180 -160 -140 -120 -100

Potential, mV (CCS)

Figure G-7.   Corrosion Potentials (Measured with Respect to a Copper/Copper Sulfate Reference Electrode) After 0.75 Hours of Depolarization Following 92 Days of Galvanic Coupling of Corrosion Probe Rings, as a Function of Depth, at the CCT Site.

Figure G-8.   Corrosion Potentials (Measured with Respect to a Copper/Copper Sulfate Reference Electrode) After 120 Days of Galvanic Coupling of Corrosion Probe Rings, as a Function of Depth, at the CCT Site.

Figure G-9.   Corrosion Potentials (Measured with Respect to a Copper/Copper Sulfate Reference Electrode) After 1 Hour of Depolarization Following 120 Days of Galvanic Coupling of Corrosion Probe Rings, as a Function of Depth, at the CCT Site.

Figure G-10.   Corrosion Potentials (Measured with Respect to a Copper/Copper Sulfate Reference Electrode) of Corrosion Probe Rings, as a Function of Depth and Time, for the CCT Site.

Figure G-11.   Corrosion Potentials (Measured with Respect to a Platinum Electrode) 3 Hours After Insertion of the Corrosion Probe, as a Function of Depth, at the CCT Site.

Figure G-12.   Corrosion Potentials (Measured with Respect to a Platinum Electrode) 24 Hours After Insertion of the Corrosion Probe, as a Function of Depth, at the CCT Site.

Figure G-13. Corrosion Potentials (Measured with Respect to a Platinum Electrode) After 120 Days of Galvanic Coupling of Corrosion Probe Rings, as a Function of Depth, at the CCT Site.

Figure G-14. Corrosion Potentials (Measured with Respect to a Platinum Electrode) After 1 Hour of Depolarization Following 92 Days of Galvanic Coupling of Corrosion Probe Rings, as a Function of Depth, at the CCT Site.

Figure G-15.   Corrosion Potentials (Measured with Respect to a Platinum Electrode) of Corrosion Probe Rings, as a Function of Depth and Time, for the CCT Site.

Figure G-16. Comparison of Corrosion Potentials Measured with Respect to a Copper/Copper Sulfate (CCS) Reference Electrode with Potentials Measured with Respect to a Platinum (Pt) Electrode Immediately After Insertion of the Corrosion Probe, as a Function of Depth, at the CCT Site.

Figure G-17. Comparison of Corrosion Potentials Measured with Respect to a Copper/Copper Sulfate (CCS) Reference Electrode with Potentials Measured with Respect to a Platinum (Pt) Electrode 49 Days and 49 Days + 0.5 Hours After Insertion of the Corrosion Probe, as a Function of Depth, at the CCT Site.

Figure G-18.   Galvanic Currents 24 Hours After Coupling Corrosion Probe Rings, as a Function of Depth, at the CCT Site.

Figure G-19.   Galvanic Currents 28 Days After Coupling Corrosion Probe Rings, as a Function of Depth, at the CCT Site.

Figure G-20.   Galvanic Currents 56 Days After Coupling Corrosion Probe Rings, as a Function of Depth, at the CCT Site.

Figure G-21.   Galvanic Currents 92 Days After Coupling Corrosion Probe Rings, as a Function of Depth, at the CCT Site.

Figure G-22.   Galvanic Currents 120 Days After Coupling Corrosion Probe Rings, as a Function of Depth, at the CCT Site.

Figure G-23. Galvanic Currents of Coupled Corrosion Probe Rings, as a Function of Depth and Time, for the CCT Site.

Figure G-24. Comparison of Corrosion Rates Calculated From Polarization Resistance (PR), Weight-Loss (W. Loss), and Galvanic Current Measurements of Field Corrosion Probe Rings, as a Function of Depth, at the CCT Site.

Figure G-25. Comparison of Corrosion Rates Calculated From Laboratory and Field Polarization Resistance (PR), Weight-Loss (WL), and Galvanic Current (GC) Measurements, with Soil Sampled at the CCT Site.

APPENDIX H

LaGuardia Airport Field Site Data

Table H-1. Analyses of Soil Sampled at the LaGuardia, New York Site.

Sample Number	Field Sample Identity	Depth, Feet	Depth, Inches	Description	Particle Size Analysis (USCS Classification)			CEC, meq/100 g [2]	pH ASTM G 51	pH ASTM D 4972		Resistivity, Ω-cm		Corrosivity [4]	Soluble Chloride, [5] mg/kg AASHTO T 291	Soluble Sulfate, [5] mg/kg AASHTO T 290	% Moisture AASHTO T 265 @ 60°C
					% Gravel	% Sand	% Fines			DI H$_2$O	CaCl$_2$H$_2$O	As-Received	Saturated				
1	LG1-A	0.0 - 1.3	15.5	Black top soil, silty sand, gravel	19.63	63.43	16.94	1.56	6.4	6.58	6.79	52,000	6,600	Mild to Low Corrosivity	N.D. [6]	68	13.08
2	LG1-B	1.3 - 3.0	36.0	Medium and fine sand	3.03	93.59	3.38	0.62	6.4	7.34	7.20	61,000	15,000	Low Corrosivity	N.D.	24	5.87
3	LG2-A	3.0 - 4.1	49.4	Medium and fine sand, slight gravel	3.70	91.29	5.01	0.52	6.1	7.48	7.30	43,000	12,000	Low Corrosivity	N.D.	35	6.89
4	LG2-C	4.1 - 5.2	62.0	Medium and fine sand, slight gravel	3.41	94.36	2.23	0.52	6.4	7.51	7.24	64,000	18,000	Low Corrosivity	N.D.	38	7.22
5	LG2-D	5.2 - 5.9	71.1	Medium and fine sand, gravel	6.02	91.86	2.12	0.31	6.6	6.89	7.00	76,000	14,000	Low Corrosivity	N.D.	16	6.94
6	LG2-E	*[1]	–	Medium and fine sand, gravel	8.40	83.51	8.09	0.69	6.8	6.93	7.00	83,000	9,000	Mild to Low Corrosivity	N.D.	N.D.	6.94
7	LG3-A	5.9 - 7.7	92.1	(Water Table @ 92") Medium and fine sand, slight gravel	2.34	93.06	4.60	0.41	6.5	7.08	7.00	37,000	8,400	Mild to Low Corrosivity	N.D.	32	9.40
8	LG3-B	7.7 - 8.9	107.1	Medium and fine sand, slight gravel	1.31	97.33	1.36	0.21	6.3	7.21	7.05	11,000	11,000	Low Corrosivity	N.D.	28	17.63
9	LG4-A	8.9 - 9.8	117.2	Medium and fine sand	0.99	96.34	2.67	0.31	6.4	7.29	7.18	11,000	8,200	Mild to Low Corrosivity	N.D.	32	17.89
10	LG4-B	9.8 - 10.0	120.5	Fine sand	0.00	97.35	2.45	I.S. [3]	6.9	7.52	7.32	I.S. [3]	I.S. [3]	–	N.D.	57	20.27
11	LG4-C	10.0 - 10.5	125.8	Medium and fine sand	0.00	90.72	9.27	0.70	6.9	6.88	6.88	1,600	1,300	Corrosive	N.D.	815	32.93
12	LG4-D	10.5 - 10.9	130.4	Medium and fine sand	0.00	98.60	1.40	0.27	6.8	7.36	7.27	12,000	10,000	Low Corrosivity	N.D.	55	20.68
13	LD4-E	10.9 - 11.9	143.1	Medium and fine sand	0.30	98.54	1.16	0.21	6.8	7.41	7.23	7,100	3,800	Mild Corrosivity	N.D.	186	17.56

[1] Four, one-inch segments from 3.2 to 3.3 feet, 4.1 to 4.2 feet, 4.5 to 4.6 feet, and 5.2 to 5.3 feet.

[2] Methylene Blue Method

[3] I.S. = Insufficient Sample

[4] Based on resistivity

[5] Corrected for moisture content of soil.

[6] N.D. = Not Detectable, <10 mg/kg

Table H-2.   Field Corrosion Probe Data From the LaGuardia Site.

Soil Sample No.	Field Probe Rings Depth, Inches	Galvanic Current[1] μA/cm² (mpy)		Polarization Resistance Ω - cm² (mpy)			Weight Loss (mpy)	Potential, mV (CCS)			
		10/25/96 19 Hours	2/4/97 103 Days	10/25/96 0.5 Hours	10/25/96 19 Hours	2/4/97 103 Days	2/4/97 103 Days	10/24/96 0.5 Hours	10/25/96 19 Hours	2/4/97 103 Days	2/4/97 103 Days, 1/2 Hours
7	72.00 - 76.00	0.056 (0.027)	0.134 (0.064)	-	-	-	1.305	-556	-680	-424	-359
7	76.38 - 80.38	0.326 (0.154)	0.657 (0.311)	-	-	-	0.857	-511	-641	-402	-316
7	80.75 - 84.75	0.195 (0.092)	0.375 (0.177)	90,847 (0.22)	110,744 (0.18)	490,244 (0.04)	1.292	-552	-680	-472	-419
7	85.00 - 89.00	0.085 (0.040)	0.175 (0.083)	-	-	-	1.537	-592	-715	-719	-718
8	98.75 - 102.75	-0.172 (-0.081)	-2.002 (-0.947)	-	-	-	0.993	-607	-724	-744	-745
8	103.00 - 107.00	-0.328 (-0.155)	-0.405 (-0.191)	-	-	-	1.006	-618	-731	-743	-746
9	107.25 - 111.75	-0.451 (-0.213)	-0.477 (-0.226)	8,645 (2.35)	18,918 (1.07)	1,740 (11.68)	0.898	-607	-734	-741	-746
9	111.50 - 115.50	0.26 (0.123)	-2.256 (-1.067)	-	-	-	0.925	-612	-723	-742	-745

[1] Positive values indicate that these rings were cathodic (non-corroding).

Figure H-1.   Graphical Representation of Soil Analysis Data for the LaGuardia Site as a Function of Depth.

Figure H-2.   Particle Size Analysis of Soil Sampled, as a Function of Depth, at the LaGuardia Site.

Figure H-3. Corrosion Potentials (Measured with Respect to a Copper/Copper Sulfate Reference Electrode) 0.5 Hours After Insertion of the Corrosion Probe, as a Function of Depth, at the LaGuardia Site.
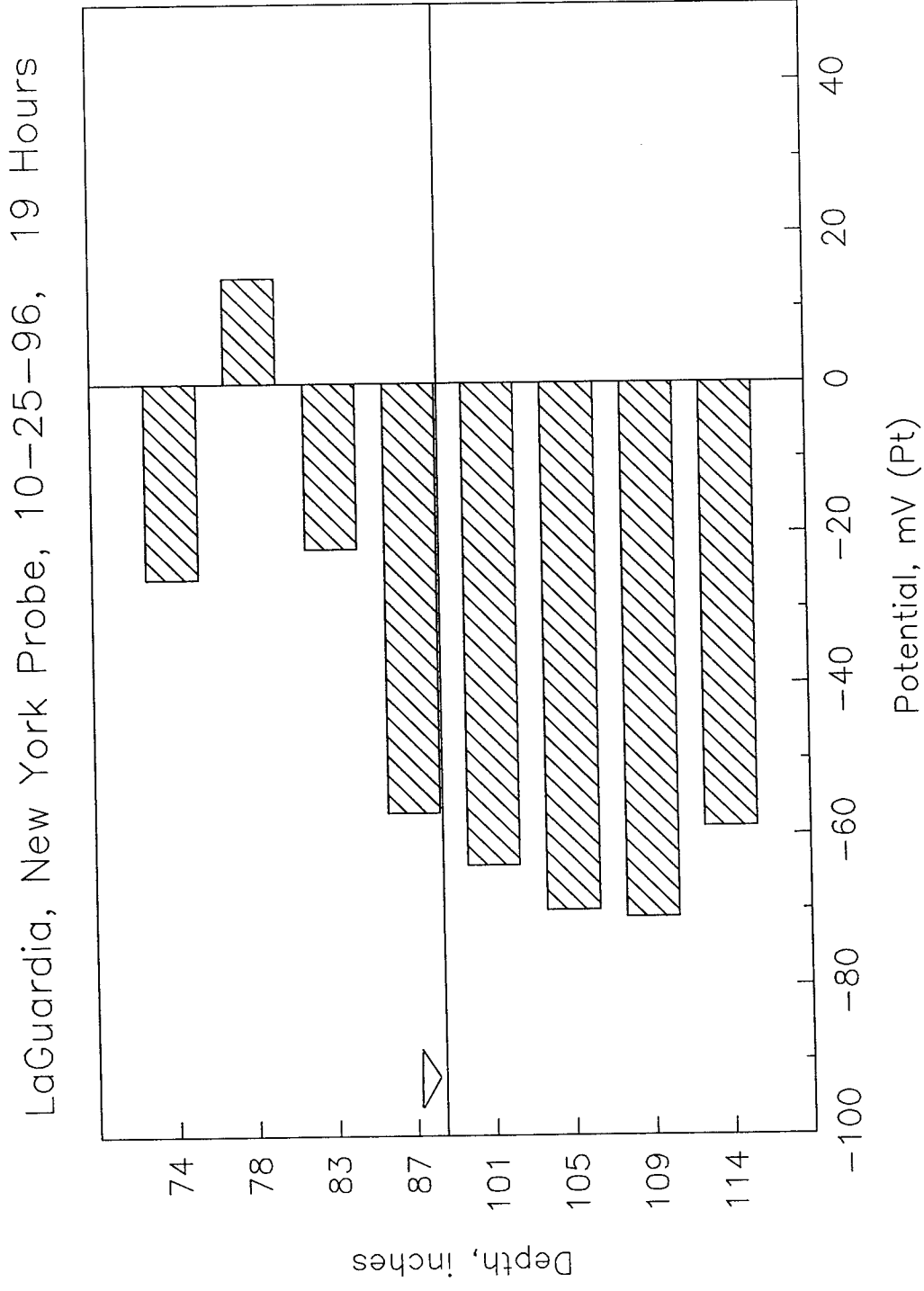
Figure H-4. Corrosion Potentials (Measured with Respect to a Copper/Copper Sulfate Reference Electrode) 19 Hours After Insertion of the Corrosion Probe, as a Function of Depth, at the LaGuardia Site.

Figure H-5.   Corrosion Potentials (Measured with Respect to a Copper/Copper Sulfate Reference Electrode) After 103 Days of Galvanic Coupling of Corrosion Probe Rings, as a Function of Depth, at the LaGuardia Site.

Figure H-6.   Corrosion Potentials (Measured with Respect to a Copper/Copper Sulfate Reference Electrode) After 30 Minutes of Depolarization Following 103 Days of Galvanic Coupling of Corrosion Probe Rings, as a Function of Depth, at the LaGuardia Site.

Figure H-7. Corrosion Potentials (Measured with Respect to a Copper/Copper Sulfate Reference Electrode) of Corrosion Probe Rings, as a Function of Depth and Time, for the LaGuardia Site.

Figure H-8. Corrosion Potentials (Measured with Respect to a Platinum Electrode) 0.5 Hours After Insertion of the Corrosion Probe, as a Function of Depth, at the LaGuardia Site.

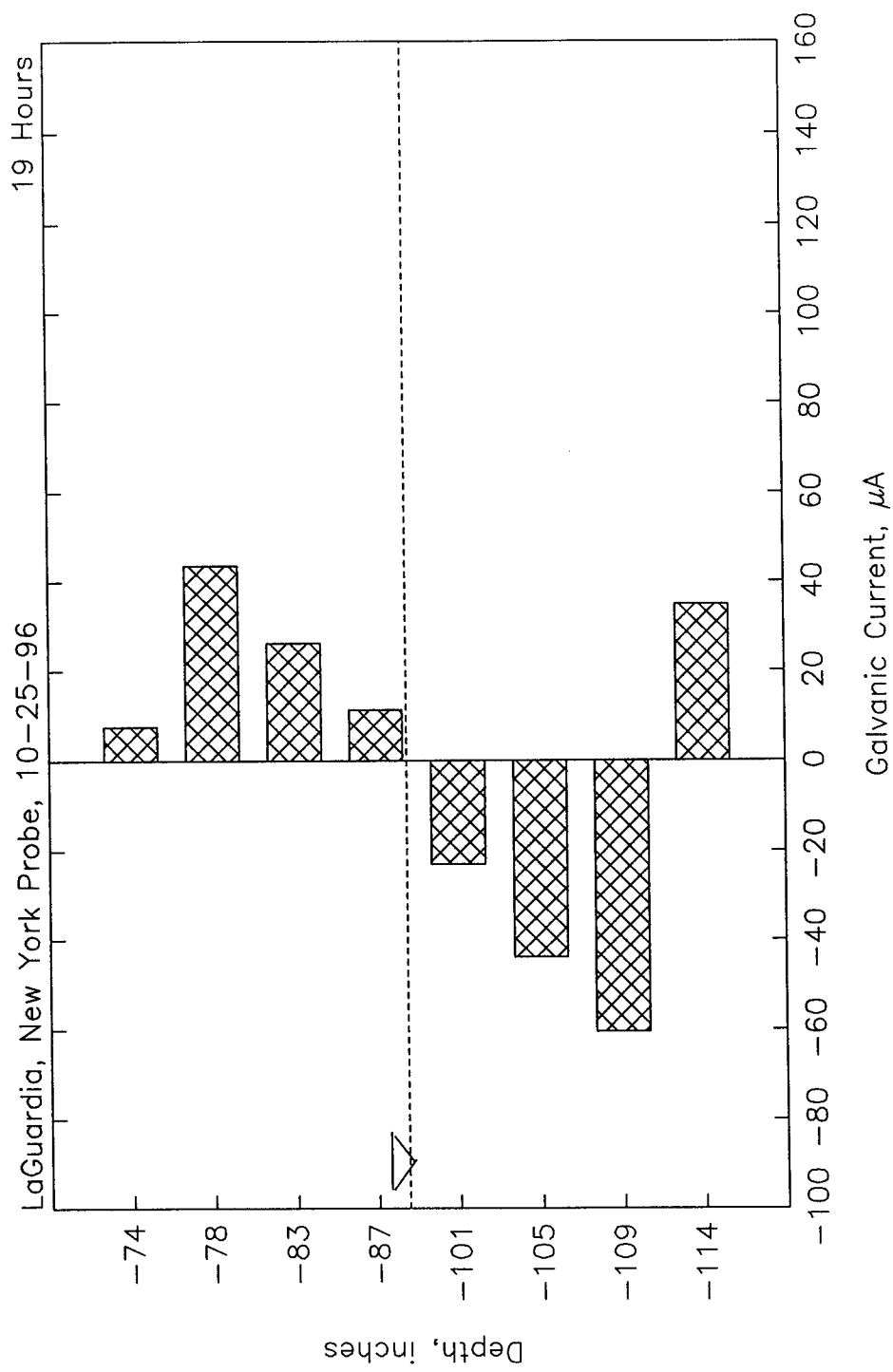Figure H-9.   Corrosion Potentials (Measured with Respect to a Platinum Electrode) 19 Hours After Insertion of the Corrosion Probe, as a Function of Depth, at the LaGuardia Site.

Figure H-10. Corrosion Potentials (Measured with Respect to a Platinum Electrode) After 103 Days of Galvanic Coupling of Corrosion Probe Rings, as a Function of Depth, at the LaGuardia Site.

Figure H-11.   Corrosion Potentials (Measured with Respect to a Platinum Electrode) After 30 Minutes of Depolarization Following 103 Days of Galvanic Coupling of Corrosion Probe Rings, as a Function of Depth, at the LaGuardia Site.
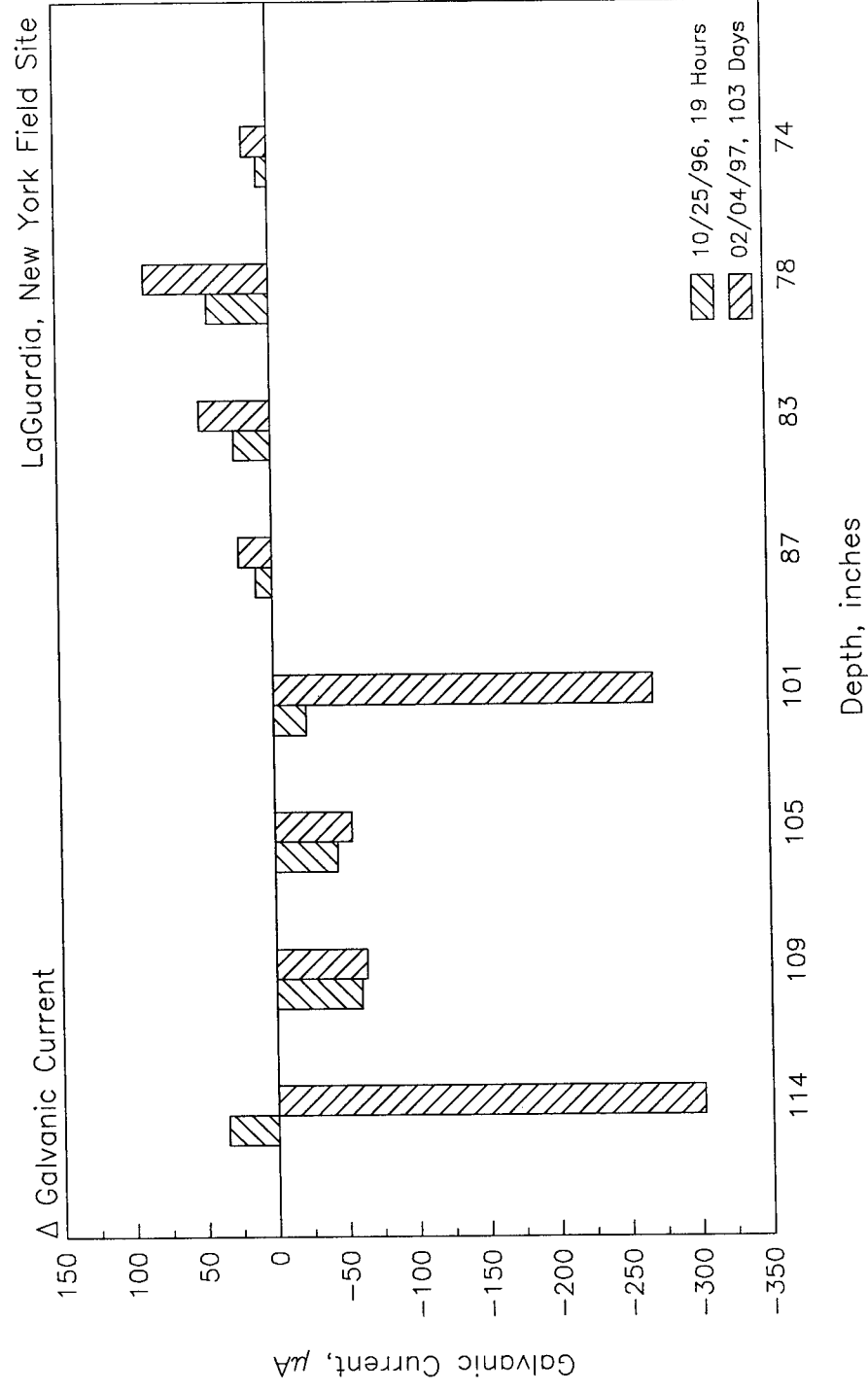
Figure H-12.   Corrosion Potentials (Measured with Respect to a Platinum Electrode) of Corrosion Probe Rings, as a Function of Depth and Time, for the LaGuardia Site.

Figure H-13. Comparison of Corrosion Potentials Measured with Respect to a Copper/Copper Sulfate (CCS) Reference Electrode with Potentials Measured with Respect to a Platinum (Pt) Electrode Immediately After Insertion of the Corrosion Probe, as a Function of Depth, at the LaGuardia Site.

Figure H-14.   Comparison of Corrosion Potentials Measured with Respect to a Copper/Copper Sulfate (CCS) Reference Electrode with Potentials Measured with Respect to a Platinum (Pt) Electrode 49 Days and 49 Days + 0.5 Hours After Insertion of the Corrosion Probe, as a Function of Depth, at the LaGuardia Site.

Figure H-15.   Galvanic Currents 19 Hours After Coupling Corrosion Probe Rings, as a Function of Depth, at the LaGuardia Site.

Figure H-16.   Galvanic Currents 103 Days After Coupling Corrosion Probe Rings, as a Function of Depth, at the LaGuardia Site.

Figure H-17.   Galvanic Currents of Coupled Corrosion Probe Rings, as a Function of Depth and Time, for the LaGuardia Site.

Figure H-18. Comparison of Corrosion Rates Calculated From Polarization Resistance (PR), Weight-Loss (W. Loss), and Galvanic Current Measurements of Field Corrosion Probe Rings, as a Function of Depth, at the Buffalo Site.

APPENDIX I

Data Comparisons at Various Field Sites

Figure I-1.   Comparative pH Data, Using Three Test Methods, for Soil Sampled at the Buffalo Site as a Function of Depth.

Figure I-2.   Comparative pH Data, Using Three Test Methods, for Soil Sampled at the CCT Site as a Function of Depth.

Figure I-3.   Comparative pH Data, Using Three Test Methods, for Soil Sampled at the LaGuardia Site as a Function of Depth.
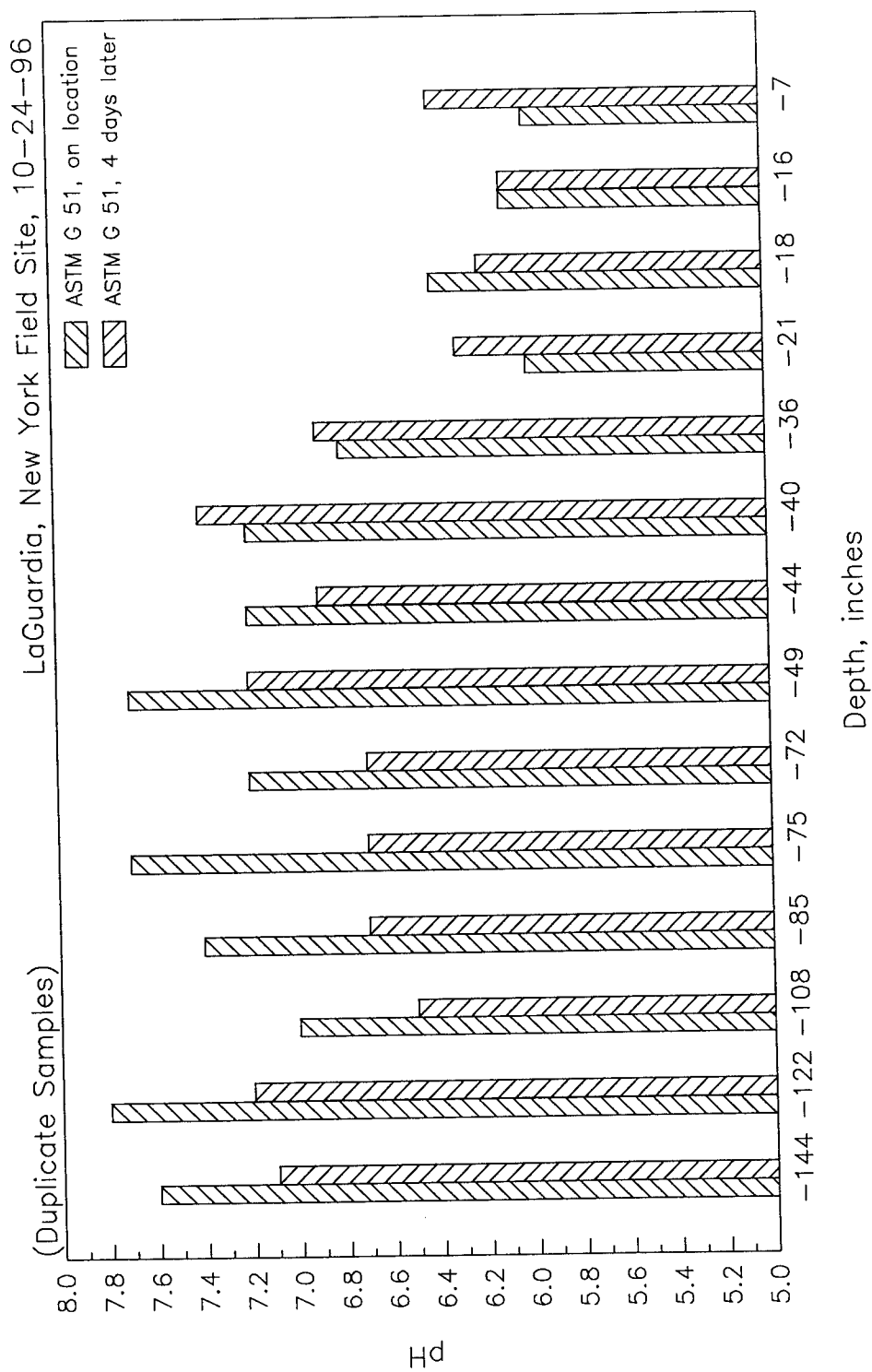
Figure I-4.   Comparison of Soil pH Measured on Location, at the LaGuardia Site, with Measurements Performed in the Laboratory, Four Days Later, Using the ASTM G 51 Test Method.
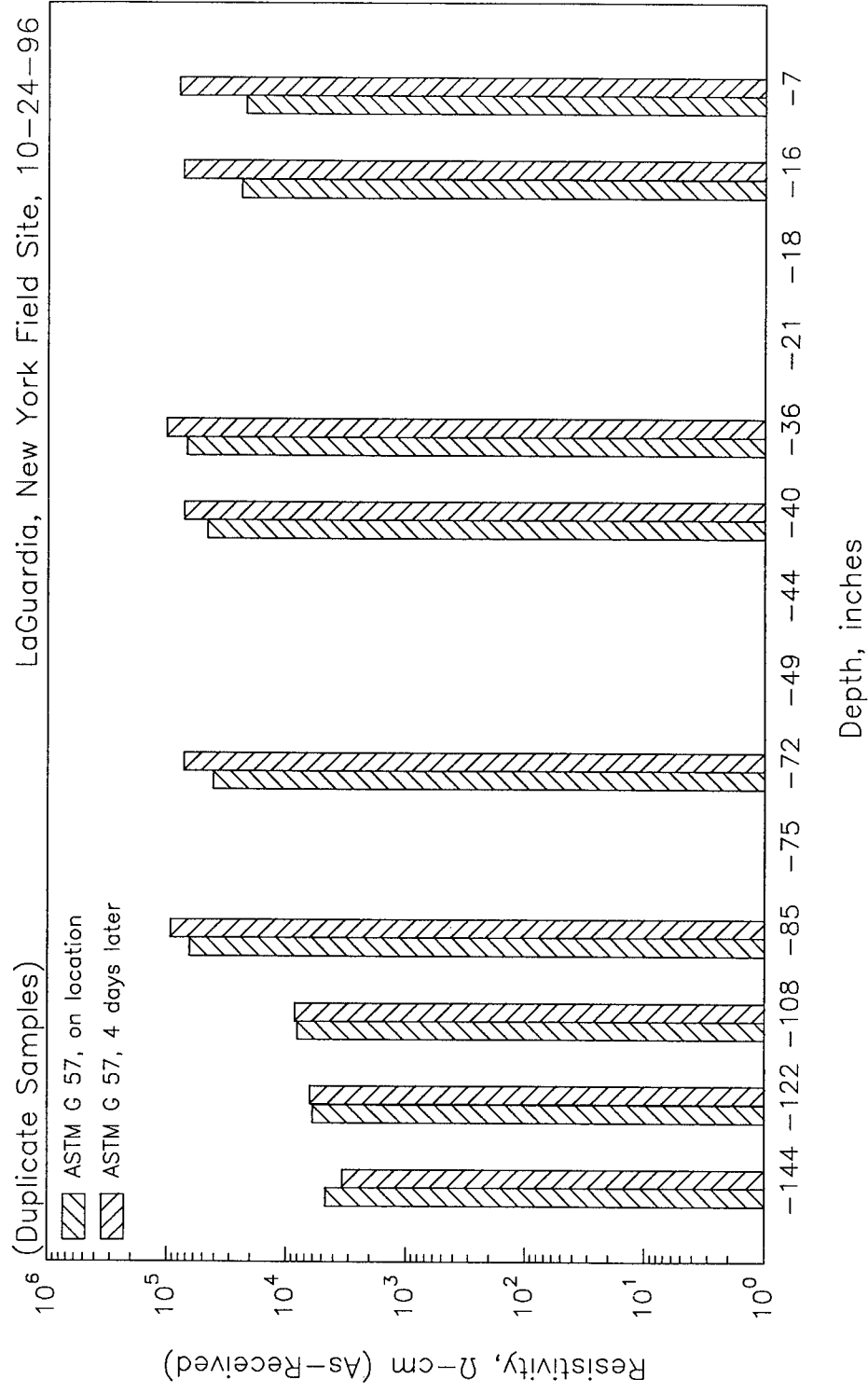
Figure I-5. Comparison of As-Received Soil Resistivity Measured on Location, at the LaGuardia Site, with Measurements Performed in the Laboratory, Four Days Later, Using the ASTM G 57 Test Method.
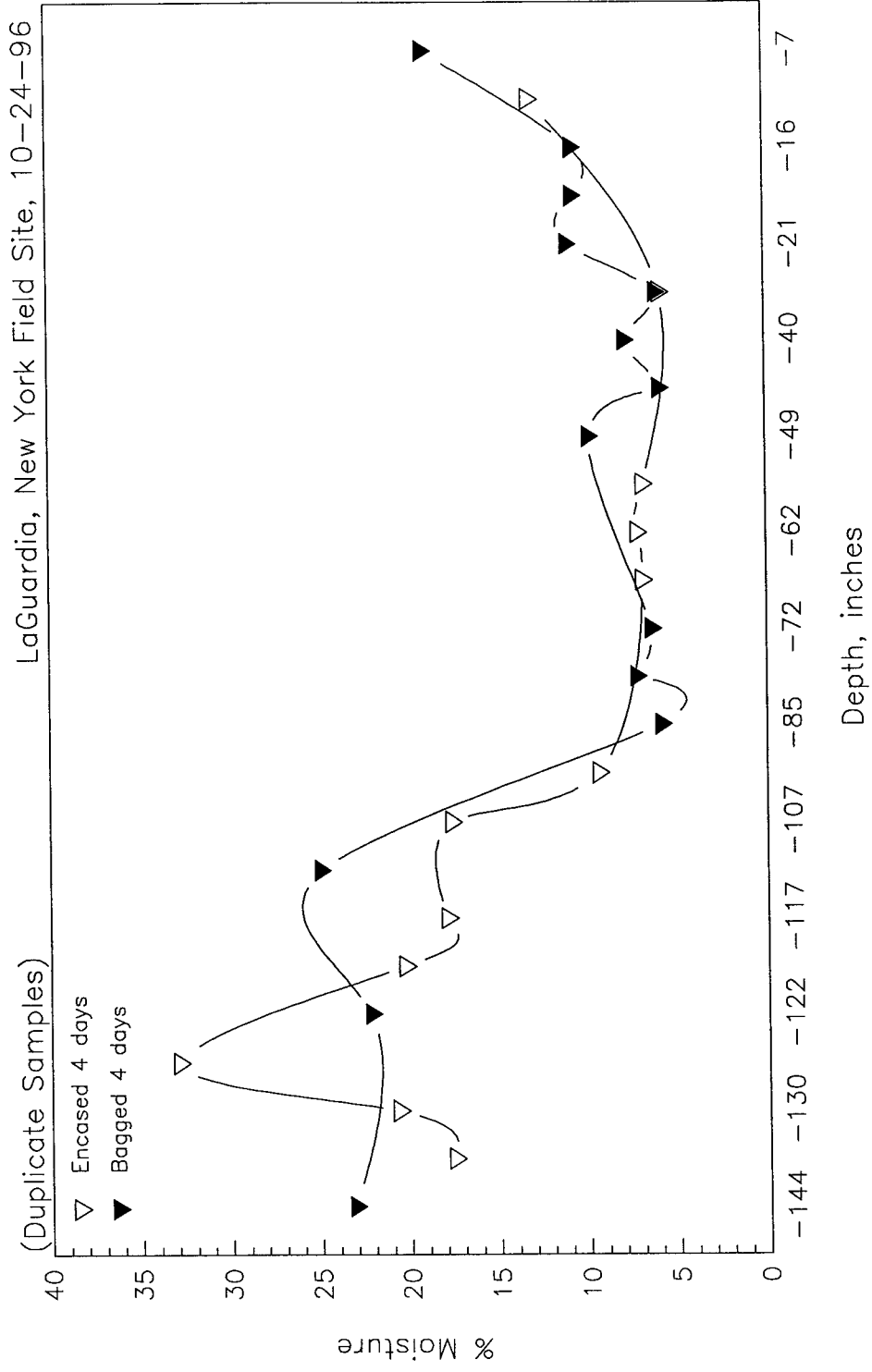
Figure I-6. Comparison of Soil Moisture Measured Four Days After Sampling, in Soil which was Encased in Plastic, with Soil which was Double-Bagged on Location. Duplicate Samples were Obtained from Borings 30 Inches Apart at the LaGuardia Site.
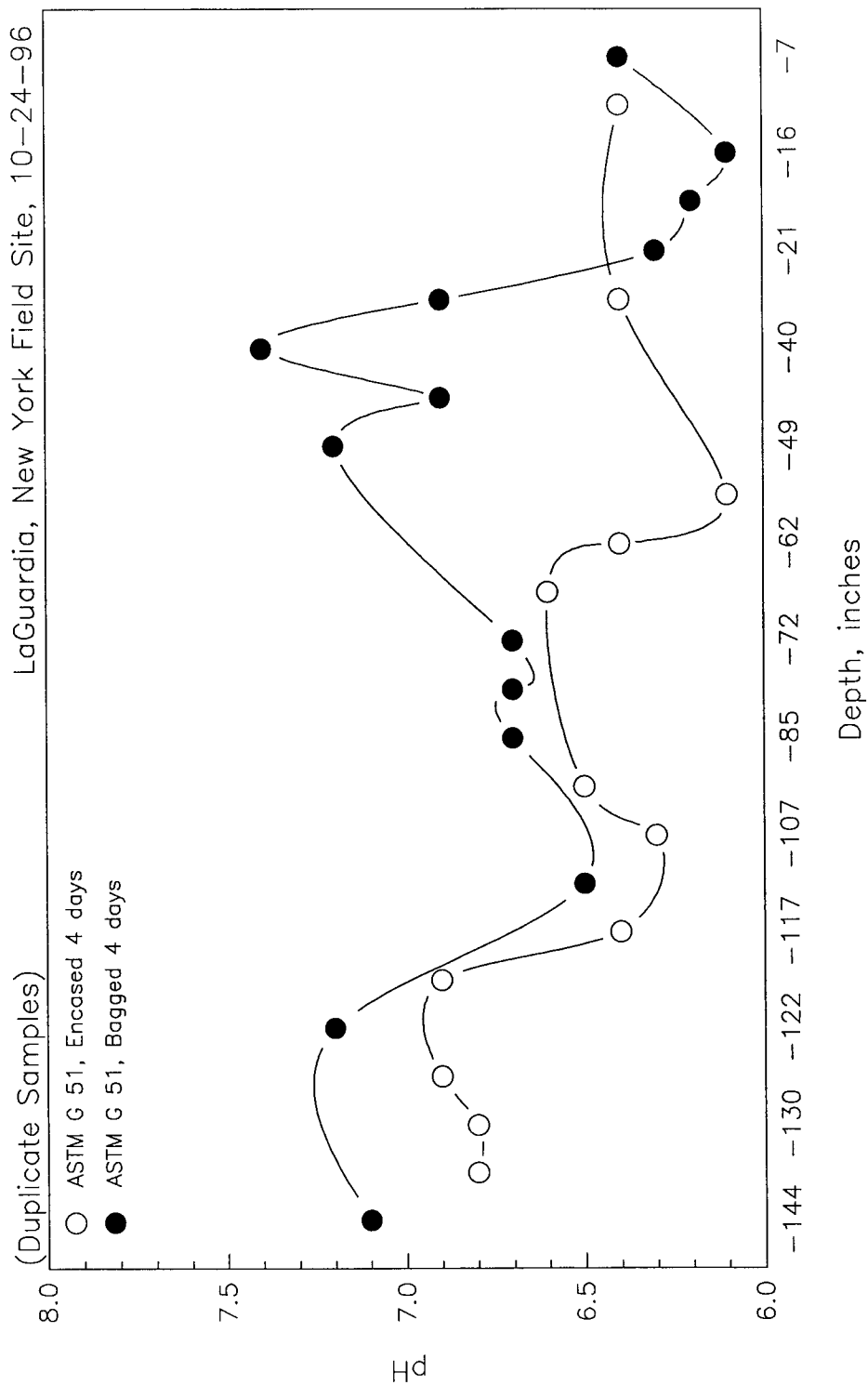
Figure I-7. Comparison of Soil pH Measured Four Days After Sampling, in Soil which was Encased in Plastic, with Soil which was Double-Bagged on Location. Duplicate Samples were Obtained from Borings 30 Inches Apart at the LaGuardia Site.
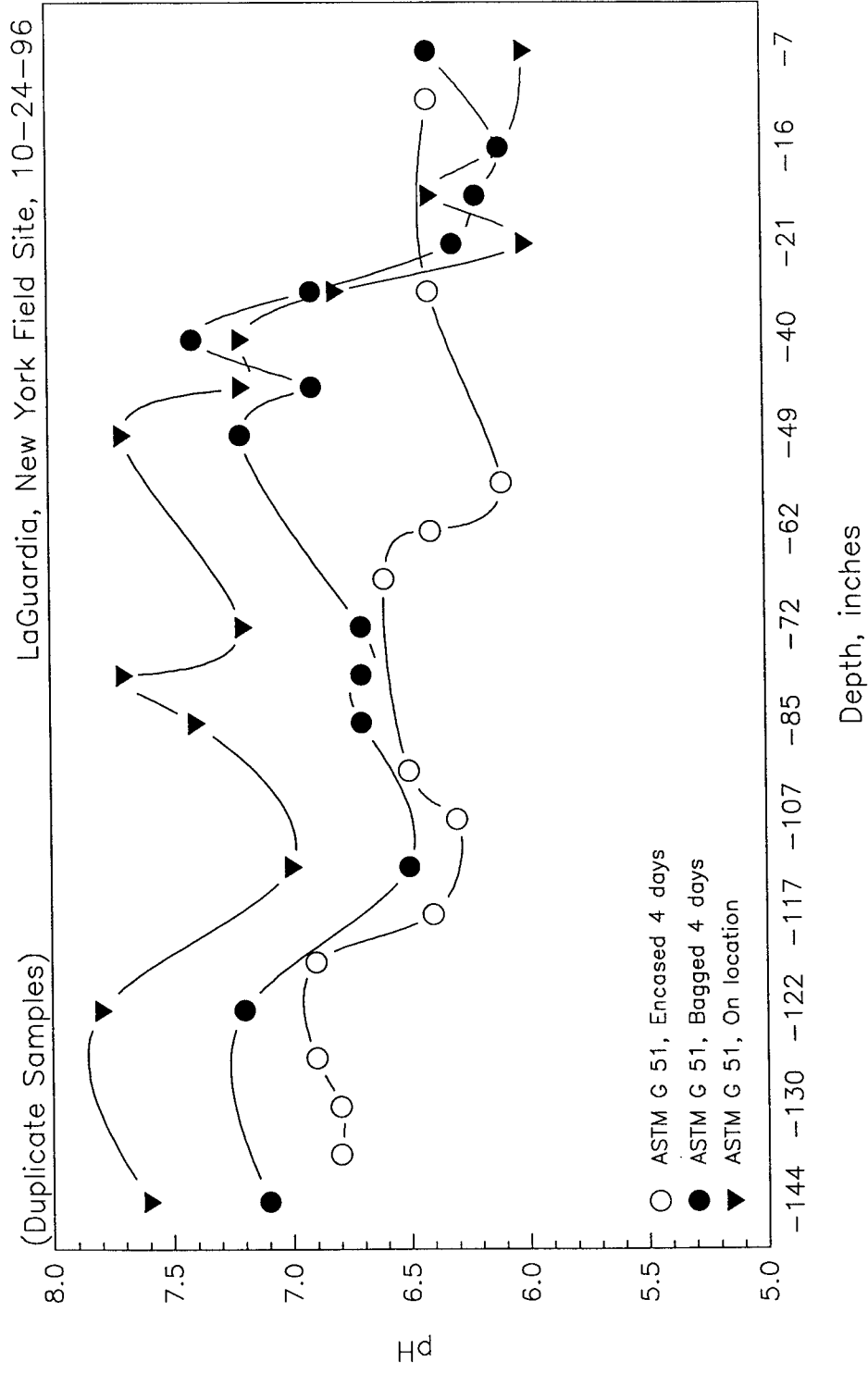
Figure I-8. Comparison of Soil pH Measured On Location and Four Days After Sampling, in Soil which was Encased in Plastic, with Soil which was Double-Bagged on Location. Duplicate Samples were Obtained from Borings 30 Inches Apart at the LaGuardia Site.

Figure I-9. Comparison of As-Received Soil Resistivity Measured Four Days After Sampling, in Soil which was Encased in Plastic, with Soil which was Double-Bagged on Location. Duplicate Samples were Obtained from Borings 30 Inches Apart at the LaGuardia Site.
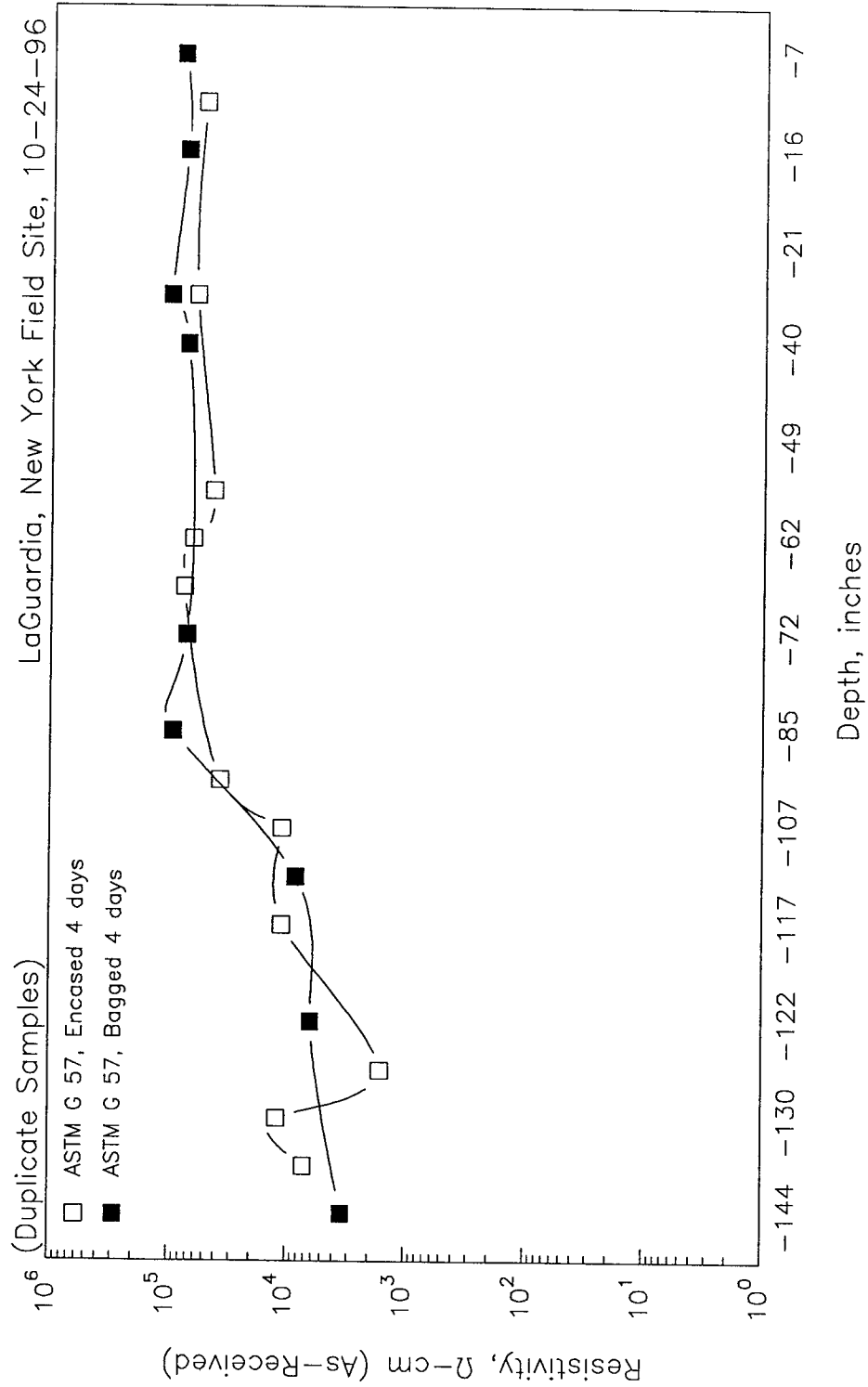
Figure I-10. Comparison of Corrosion Potentials Measured with Respect to a Copper/Copper Sulfate (CCS) Reference Electrode with Potentials Measured with Respect to a Platinum (Pt) Electrode Immediately After Insertion of the Corrosion Probe, as a Function of Depth, at the Buffalo Site.
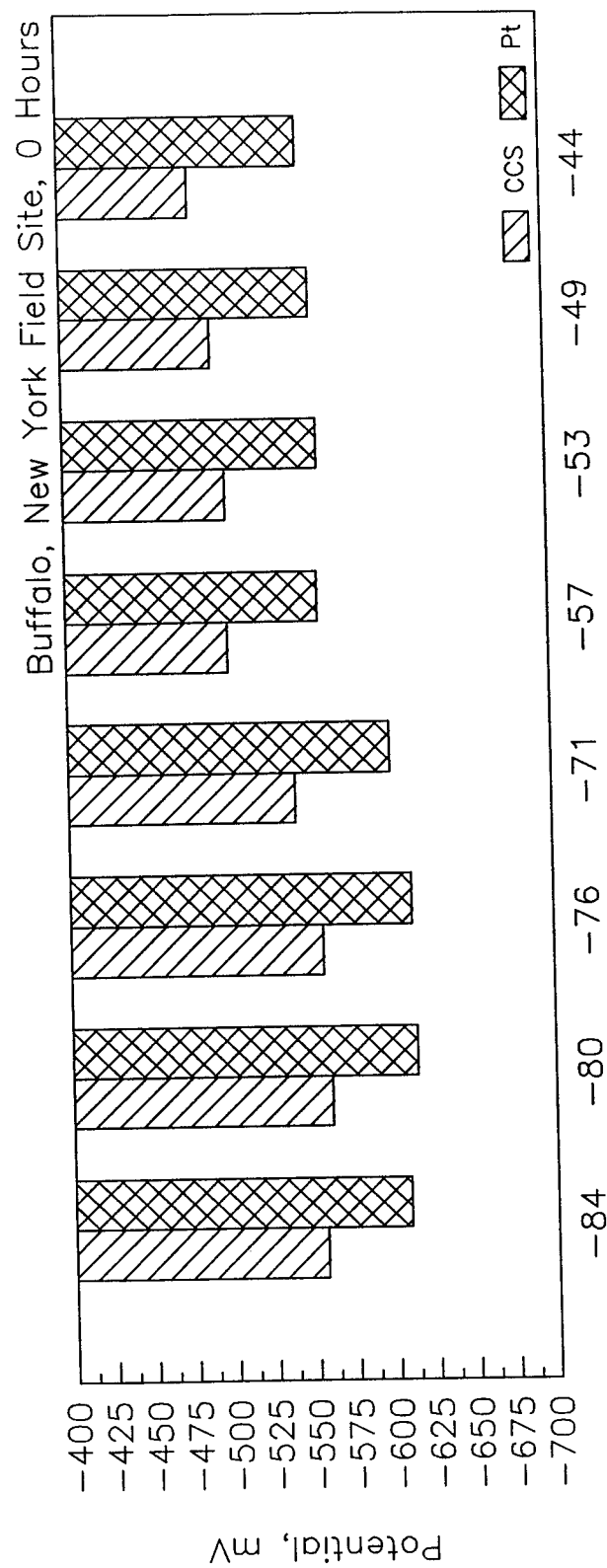
Figure I-11. Comparison of Corrosion Potentials Measured with Respect to a Copper/Copper Sulfate (CCS) Reference Electrode with Potentials Measured with Respect to a Platinum (Pt) Electrode 49 Days (and After 0.5 Hours of Depolarization) After Insertion of the Corrosion Probe, as a Function of Depth, at the Buffalo Site.

Figure I-12. Comparison of Corrosion Potentials Measured with Respect to a Copper/Copper Sulfate (CCS) Reference Electrode with Potentials Measured with Respect to a Platinum (Pt) Electrode 3 Hours and 24 Hours After Insertion of the Corrosion Probe, as a Function of Depth, at the CCT Site.
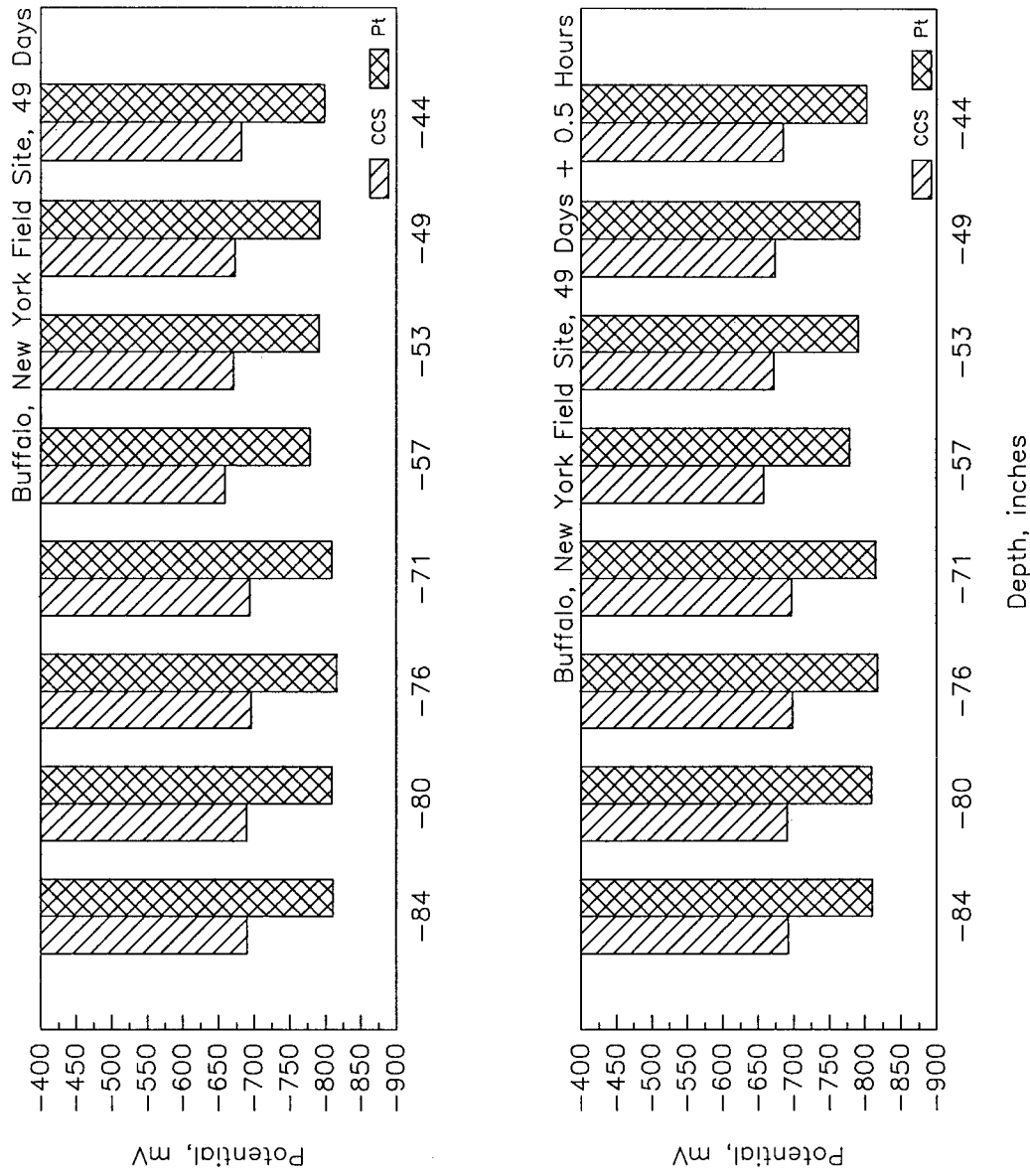
Figure I-13.   Comparison of Corrosion Potentials Measured with Respect to a Copper/Copper Sulfate (CCS) Reference Electrode with Potentials Measured with Respect to a Platinum (Pt) Electrode 120 Days (and After 1 Hour of Depolarization) After Insertion of the Corrosion Probe, as a Function of Depth, at the CCT Site.
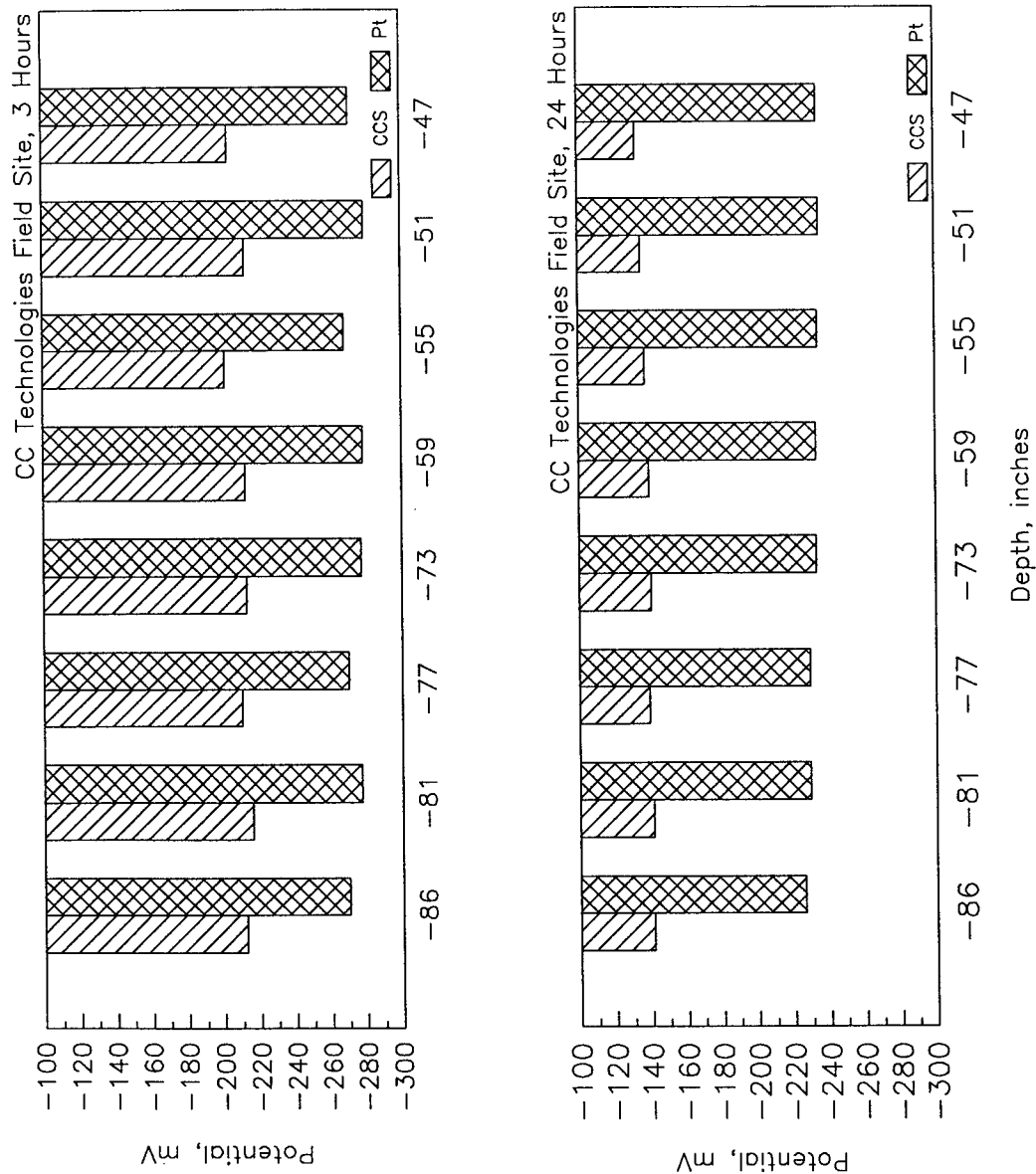
Figure I-14.   Comparison of Corrosion Potentials Measured with Respect to a Copper/Copper Sulfate (CCS) Reference Electrode with Potentials Measured with Respect to a Platinum (Pt) Electrode 0.5 Hours and 18 Hours After Insertion of the Corrosion Probe, as a Function of Depth, at the LaGuardia Site.
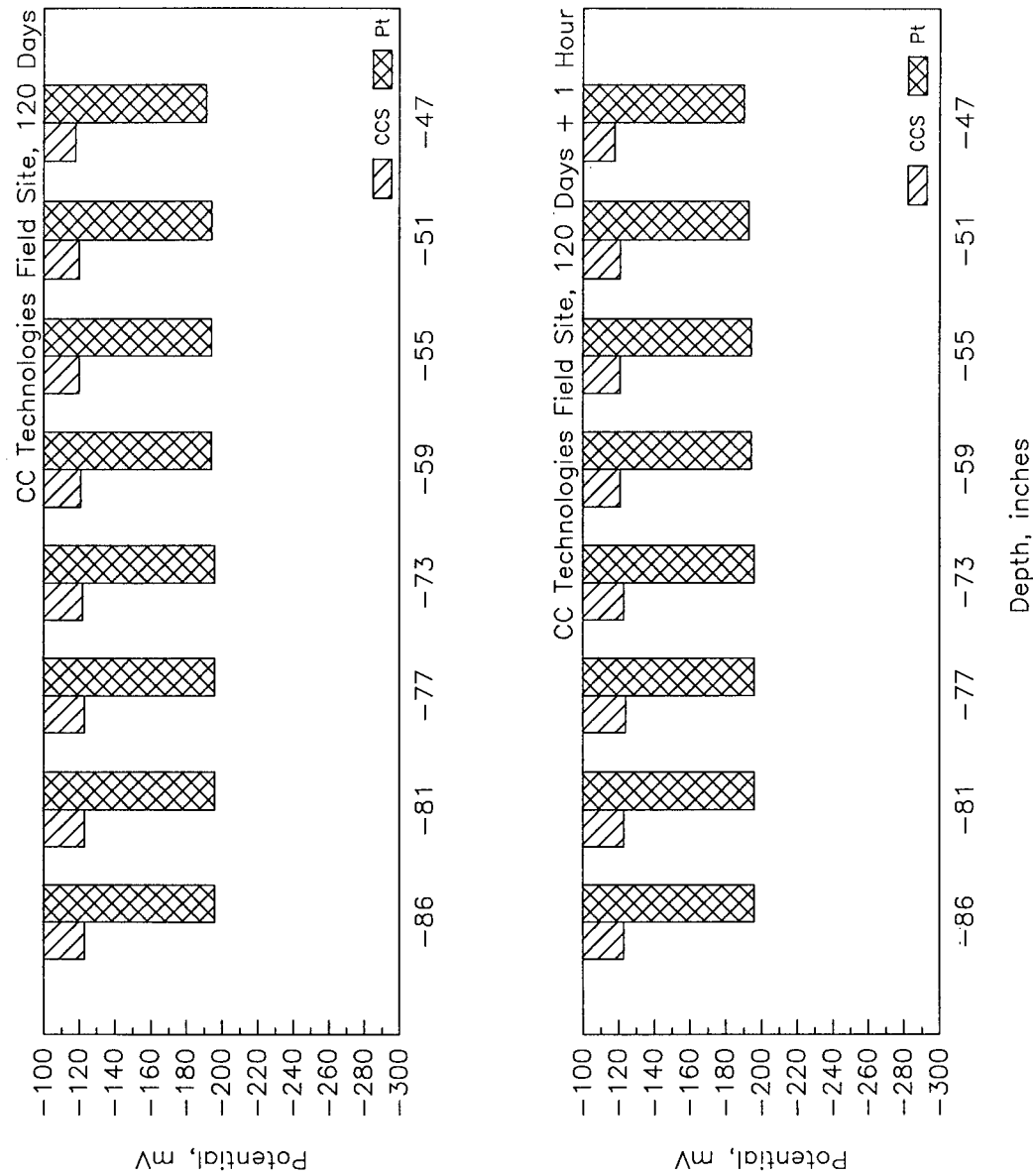
Figure I-15. Comparison of Corrosion Potentials Measured with Respect to a Copper/Copper Sulfate (CCS) Reference Electrode with Potentials Measured with Respect to a Platinum (Pt) Electrode 103 Days (and After 0.5 Hours of Depolarization) After Insertion of the Corrosion Probe, as a Function of Depth, at the LaGuardia Site.
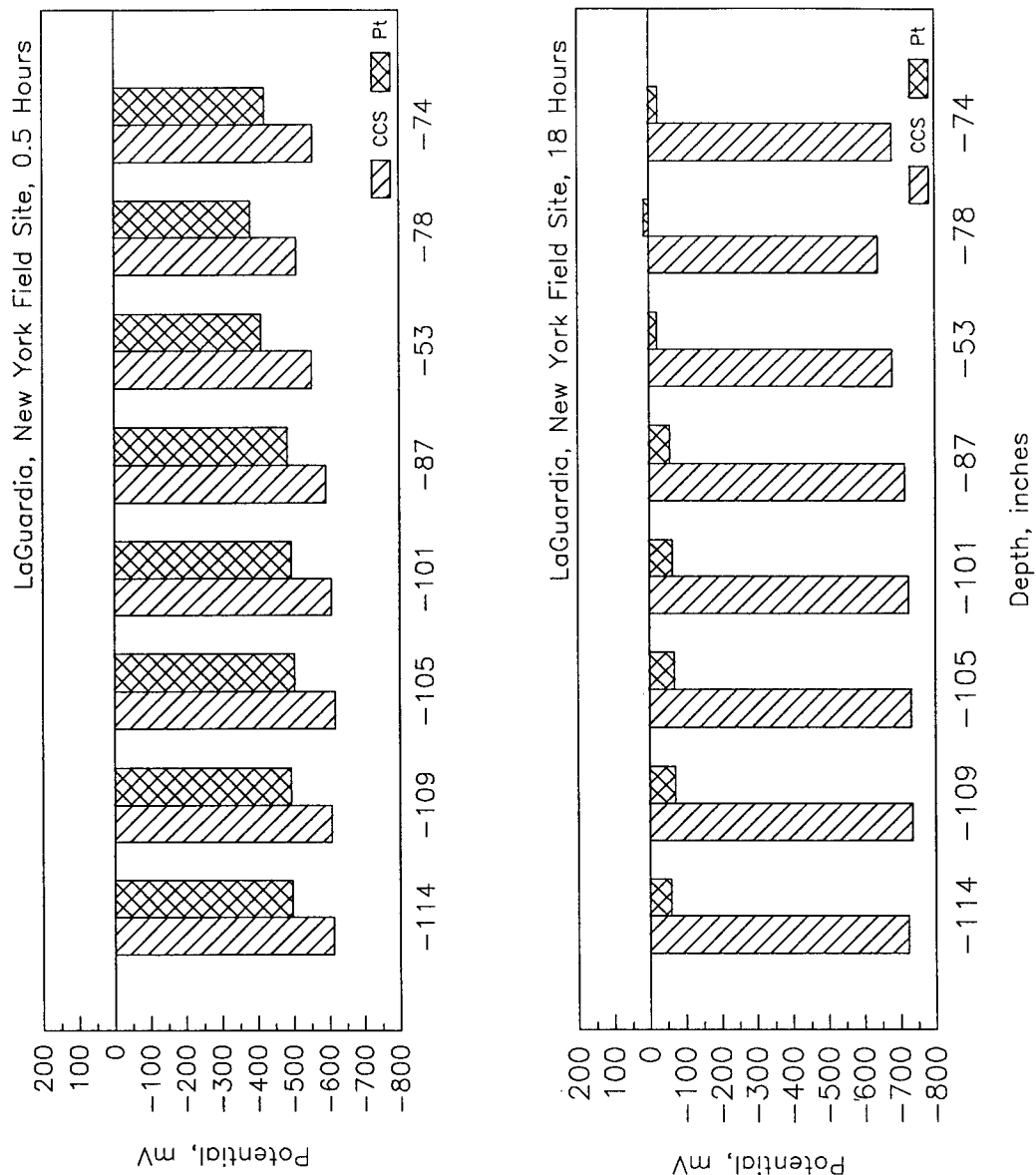
Figure I-16. Comparison of Corrosion Rates Calculated from Laboratory and Field Polarization Resistance, Galvanic Current, and Weight-Loss Measurements of Soil from the Buffalo Site.

Figure I-17. Comparison of Corrosion Rates Calculated from Laboratory and Field Polarization Resistance, Galvanic Current, and Weight-Loss Measurements of Soil from the CCT Site.

APPENDIX J

Appendix J, "Modeling," is not published herein. Copies may be obtained on request to NCHRP.

APPENDIX K

Appendix K, "Final Recommended Practice," is not published herein. Copies may be obtained from AASHTO by referencing AASHTO Provisional Standard PP36-97.

APPENDIX L

Justification for Soil Handling, Description, and Testing Methodology Modifications of AASHTO and ASTM Procedures

Justification for Soil Handling, Description, and Testing Methodology Modifications of AASHTO and ASTM Procedures

Information in this appendix is the justification and reasoning for selecting and modifying test methodology referenced in the AASHTO Standard Recommended Practice for Assessment of Corrosion of Steel Piling for Non-Marine Applications. Each topic for discussion references the appropriate section in the Recommended Practice.

1.0 SOIL COLLECTION (Section 5.2)

1.1 The objective of sampling is to obtain a representative portion of the subsurface having the orientation, physical, and chemical properties of the in situ soil. The size and type of soil samples obtained are dependent upon the type and number of tests to be performed and the particle size distribution of the soil. Most of the soil tests outlined in the Practice are performed on soil particle sizes less than 4.75 mm (No. 4 sieve). Thus, fewer samples may be needed to obtain the required volume of soil necessary for testing than if the −2 mm size was used as specified in ASTM and AASHTO test methods.

1.2 Soil collection methods which cause the least soil disturbance are preferred. Man-made, landfill, and non-homogeneous soils have the greatest tendency toward corrosivity. Of primary concern are dissimilar soil layers within the vertical soil column which may lead to macrocell corrosion (galvanic attack) of bare steel piles. Thus, any soil collection methods which would preserve the integrity of soil layers are preferred.

1.3 Air is the preferred drilling fluid if split-barrel or core-drilled collection methods are used. Drilling muds and water should not be used as these fluids will contaminate the soil by dissolving soluble salts which are pertinent to the assessment of soil corrosivity.

1.4 Thin-walled tubes should not be coated with oil or any other material which may contaminate the soil sample for the same reasons as given in the above paragraph.

2.0 SAMPLE REDUCTION (Section 5.4.1)

2.1 The purpose of riffling or quartering is to reduce a large volume of soil to a workable volume while retaining properties representative of the soil mass. Visual examination, identification, and thickness of soil layers should be recorded, resistivity measurements should be made, and the pH should be determined, prior to riffling or quartering the sample.

3.0 DESCRIPTION AND IDENTIFICATION (Section 5.4.2)

3.1 The Unified Soil Classification System (USCS) was chosen because of the greater number of subdivisions used to classify coarse-grained particles. From the stand point of corrosion, the soil being tested should be representative of the particle size distribution found in the field. Thus, the soil test methods outlined in the procedures to follow utilize a particle size of less than 4.75 mm (No. 4 sieve) which is the USCS division between fine gravel and coarse sand.

3.2 The USCS System is used by the American Society for Testing and Materials (ASTM) and in many engineering applications. The primary difference between the two systems is the subdivision of gravel and sand. AASHTO's gravel (76.2 mm – 2 mm) is subdivided by USCS into coarse gravel (76.2 mm – 19.05 mm), fine gravel (19.05 mm – 4.75 mm), and

coarse sand (4.75 mm – 2.00 mm). AASHTO's coarse sand (2.00 mm – 425 µm) is equivalent to medium sand as defined by the USCS. These differences are illustrated in Figure L-1.

4.0 pH (Sections 5.2.5.1 and 5.4.4))

4.1 Soil pH is considered to be one of the primary controlling factors in underground corrosion. In low-pH environments, the protective corrosion product films on steel are destabilized, resulting in localized corrosion or accelerated uniform corrosion. Where the pH is below about 4, rates of hydrogen ion reduction are sufficiently high to increase rates of corrosion. On the other hand, steel develops protective passive films in alkaline environments.

4.2 ASTM G 51 Method, *Standard Test Method for pH of Soil for Use in Corrosion Testing*, is recommended for determining the pH of primarily medium- to fine-grained soils. This method is designed to be used in the field and relies on a sufficient amount of soil moisture being present to achieve stable, accurate pH measurements across the liquid junction of the electrode thus it is not reliable for coarse-textured soils. The pH measured by this method overestimates the activity of the hydrogen ions in solution due to the excessive soil-particle-pH probe contact. Thus a lower pH would be expected using this method compared with values determined by ASTM Method D4972 and ASTM standards.[1]

4.3 ASTM Method D 4972 was chosen to determine the pH primarily of coarse-grained soils rather than AASHTO Method T 289 or ASTM Method G 51. The pH value measured with this technique should be reduced by 0.5 to 1 pH unit for comparison with pH measured by ASTM Method G 51.

4.3.1 In ASTM Method D 4972, soil pH is measured in both distilled or deionized water and in a dilute salt solution. AASHTO Method T 289 uses a 1:1 soil water slurry similar to the ASTM Method D 4972, but only measures pH in a deionized/distilled water slurry. "Soil pH measured in water is the pH closest to the pH of soil solution in the field, but is dependent on the degree of dilution (the soil-to-solution ratio)."[2] The dilute salt solution (0.01 M CaCl$_2$) is also used because of the advantages cited by Hendershot and Lalande:[2] (1) the pH is almost independent of the soluble salt concentration for non-saline soils; (2) because the suspension remains flocculated, errors due to the liquid junction potential are minimized; and (3) no significant differences in soil pH determination are observed for moist or air-dried soil.

4.3.2 A decrease of about 0.5 pH units is expected from the test using calcium chloride as compared with the pH obtained using deionized or distilled water due to displacement of some of the exchangeable aluminum, which then hydrolizes in solution.[3]

4.3.3 ASTM Method D 4972 notes possible interferences to pH measurement due to a sedimentation potential or suspension effect, but further states that these effects can be mitigated by measuring pH when the electrode is placed in partially settled suspension.

4.3.4 Particle sizes less than 4.75 mm were chosen rather than the −2 mm size given in the ASTM and AASHTO Methods. The larger particle size was selected for the following reasons: (1) All other tests are being performed on −4.75 mm particles, (2) A limited volume of soil −2 mm may be available in non-homogeneous soils, and (3) ASTM Method D 4972 allows for soil fraction with particles larger than 2 mm as long as the size is stated in the report.

5.0 RESISTIVITY (Section 5.4.3)

5.1 Soil resistivity is generally considered to be a significant factor in underground corrosion of steels. Typical guidelines for soil corrosivity are:[4]

0 to 1000 ohm–cm	Very Corrosive
1000 to 2000 ohm–cm	Corrosive
2000 to 10 000 ohm–cm	Mildly Corrosive
above 10 000 ohm–cm	Progressively Less Corrosive

Long[5] investigated the macrocell corrosion of steel pilings and concluded that where severe corrosion occurred, contiguous layers of soil had resistivities below 1000 ohm–cm.

5.2 ASTM Method G 57, Wenner Four-Pin technique was chosen for all soil resistivity measurements. The four-pin technique gives more reliable and consistent measurements compared with the results obtained from the two-pin technique described in AASHTO Method T 288. The two-pin technique is less accurate because of polarization effects.

5.3 ASTM Method G 57 is also preferable to the AASHTO Method due to its simplicity. The AASHTO Method requires incremental water additions and resistivity measurements which is a time-consuming process. The ASTM Method, on the other hand, is used to measure resistivity only on as-received and saturated soils. The saturated resistivity value is used as a "worst-case" resistivity value.

5.4 Resistivity measurements should be done in the field using the ASTM Method, but samples will need to be sent to a laboratory for saturated soil resistivity measurements.
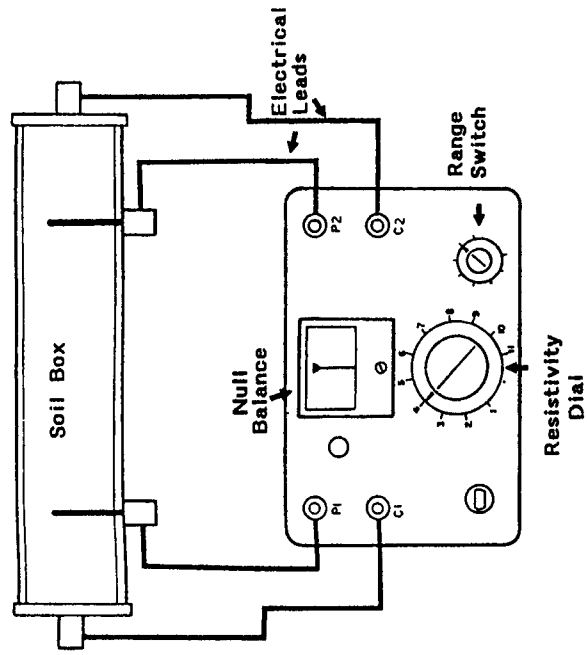
5.5 A soil resistance meter which generates a 97 Hz (alternating current) square wave is the preferred instrumentation for resistivity measurement. (See **Figure L-2** for an example of a typical meter.)

REFERENCES

1. ___, Annual Book of ASTM Standards, American Society for Testing and Materials, Philadelphia, Pennsylvania, Vol. 04.08, 1992.

2. Hendershot, W. H. and H. Lalande, "Soil Reaction and Exchangeable Acidity," Soil Sampling and Methods of Analysis, Ed: M. R. Carter, Lewis Publishers, 1993, pp. 141-144.

3. Gee, G. W. and J. W. Bauder, "Particle Size Analysis," Methods of Soil Analysis, Part I, Physical and Mineralogical Methods, Ed: A. Klute, Soil Science of America, Madison, Wisconsin, 1986, p. 384.

4. ___, "Basic Course, Appalachian Underground Corrosion Short Course," West Virginia University, Morgantown, WV, 1985.

5. Long, R. P. and F. C. Huang, "Corrosion of Driven Steel Piles," Final Report, JHR 90-193, Department of Civil Engineering, University of Connecticut, Storrs, CT, Connecticut Department of Transportation, May 1990.

6. ___ Nilsson Model 400 Four Pin Soil Resistance Meter Instruction Manual, p.5.

Sieve	mm	USCS	AASHTO
None	.0002	Fines (Silt & Clay)	Silt – Clay
No. 200	0.075	Fine Sand	Fine Sand
No. 40	0.425	Medium Sand	Coarse Sand
No. 10	2.00	Coarse Sand	
No. 4	4.75	Fine Gravel	Gravel
3/4"	19.05	Coarse Gravel	
3"	76.2	Cobbles	Boulders & Cobbles

Figure L-1   Comparison of USCS and AASHTO Soil Classification Systems.

P1, P2 = Potential-Carrying Electrodes   C1, C2 = Current-Carrying Electrodes

Figure L-2   Typical Connection for Use of Soil Box with a
Typical Soil Resistance Meter.[6]

APPENDIX M

Procedure for Measuring Galvanic Currents in a Soil Environment

PROCEDURE FOR MEASURING GALVANIC CURRENTS IN A SOIL ENVIRONMENT

1.0 SCOPE

1.1 This document describes the procedure for measuring galvanic currents with a corrosion probe in a soil environment.

2.0 PURPOSE

2.1 The purpose of this document is to establish a field procedure for measuring galvanic current between corrosive soil layers, as defined from laboratory test results. The results of the measurements are used to identify potential areas in the soil where severe corrosion may occur in steel piling in contact with those areas. Long-term measurements are used to help assess the service life of steel piling and as an indicator as to when corrosion mitigation procedures should be considered.

3.0 SIGNIFICANCE

3.1 Corrosion can occur from galvanic current flow on a metallic surface exposed to soil layers having differential oxygen concentrations or ionic strengths (macrocells). Disturbed, non-homogeneous, landfill, man-made, or highly stratified unsaturated soils are likely candidates for macrocell development. When bare steel piles are driven through these types of soil, anodic (corroding) sites develop on the pile adjacent to fine grained, poorly drained, and/or low resistivity strata. Likewise, cathodic areas develop on the pile adjacent to coarse-grained, well-drained, and/or high resistivity strata. Ionic current flow can become significant between the anodes and cathodes and eventually lead to severe corrosion. In fact, all of the severe cases of piling corrosion reported in the literature have been in highly-stratified soils. Macrocells may also develop in steel piling which straddle the water table.

4.0 APPLICABLE DOCUMENTS

4.1 Schaschl, E. and G. A. Marsh, "Some New Views on Soil Corrosion," Materials Protection, Vol. 2, No. 11, November 1963, p. 16.

4.2 Long, R. P., J. Badinter, and P. R. Kambala, "Investigation of Steel Pile Foundation in Corrosively Active Areas," Connecticut Department of Transportation, Report No. JHR 95-239, March 1995, pp. 54, 92.

4.3 Appendix P, NCHRP 10-46 Final Report (published herein).

5.0 EQUIPMENT

5.1 Corrosion Probe.

5.2 Zero resistance ammeter or equivalent.

5.3 High impedance voltmeter.

5.4 Electrical leads.

5.5 Boring tool.

6.0 USE

6.1 A corrosion probe consisting of several electrically isolated rings is used to measure galvanic current. An example of a corrosion probe is shown in Figure M-1. The separate rings enable galvanic current measurements to be performed at various depths in the soil. Electrically coupling the rings together serves to simulate a pile extending vertically through the soil. Uncoupling one of the various rings allows characterization of that specific isolated area of the simulated pile. The direction of the galvanic current measured between the isolated ring and the remaining coupled rings indicates whether that area is an anodic or cathodic site on the simulated pile.

6.2 The corrosion probe should be used where the steel pile is designed to be at, or extend both above and below the water table, through soils having test results indicating a moderate to high possibility of macrocell corrosion.

6.3 A qualified corrosion specialist should be consulted to assist in probe selection and field corrosion rate measurements.

6.4 Galvanic currents should be measured periodically to ascertain macrocell development.

6.4.1 The frequency of measurements and test duration should be established by the person(s) conducting the test on a site-specific basis.

6.4.2 For long-term corrosion monitoring, repeat measurements periodically, over the life of the pile, at intervals to be determined based on the test results.

7.0 PROCEDURE FOR PROBE PLACEMENT

7.1 Measure the surface area of each probe ring and express the values in square centimeters.

7.2 Measure the vertical distance to the top of each probe ring such that the probe may be placed at the desired depth and the depth of each ring is known.

7.3 Bore a small diameter hole (less than the diameter of the probe) in the soil to within 30 cm of the desired depth to aid in probe placement.

7.4 Install the probe in the small diameter hole such that it extends through the most corrosive layers, based on the results of the soil analyses.

7.4.1 A rotary hammer drill has been used successfully to place the probe shown in Figure M-1. The chosen placement technique should not damage the threaded ends of the probe or extensions.

7.4.2 Bring electrical leads up through extension joints if required.

7.4.3 Install a non-metallic test box on top of the last extension joint (if used) to house the electrical wires from each of the probe rings.
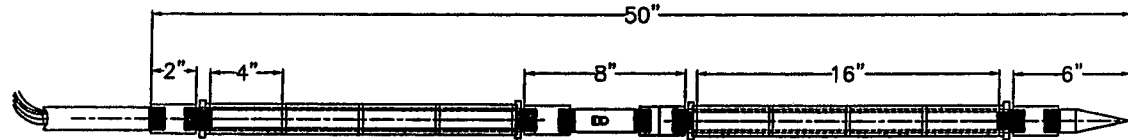
8.0 GALVANIC MEASUREMENTS

8.1 Measure the corrosion potential of each probe ring with respect to a reference electrode if included in the corrosion probe. (See Appendix P.)

8.2 Electrically short all probe wires together.

8.3 Measure the galvanic current between each steel ring and the remaining shorted ring. Note the sign of the current.

    8.3.1 Uncouple the first ring from the other rings and measure galvanic current with a zero resistance ammeter or equivalent. Recouple the ring.

        8.3.1.1 The direction (sign) of the potential difference between the isolated ring and the remaining ring may serve as a verification of the galvanic current direction.

    8.3.2 Uncouple the second ring and measure galvanic current as indicated above. Recouple the ring.

    8.3.3 Continue to uncouple successive rings and measure galvanic current.

9.0 REPORTING

9.1 Convert galvanic current measurements to current density in units of microamps/square centimeter.

9.2 Plot probe ring depth as a function of current density. See example of a typical plot in **Figure M-2**.

    9.2.1 Large galvanic currents indicate the potential for macrocells.

    9.2.2 Sign reversal of current density measurements on adjacent coupons also indicate the potential for macrocells such as shown for rings on either side of the water table in **Figure M-2**.

9.3 Galvanic current density may be converted to corrosion rate to help assess service life of the piling. For UNS K02600 (A36 mild steel):

$$\mu m/y = (\mu A/cm^2) \times (12.0086)$$

$$mpy = (\mu m/y) / 25.4$$

where $\mu m/y$ = micrometers per year

    m p y = mils per year

Figure M-1   Example of a Field Corrosion Probe for Soil.
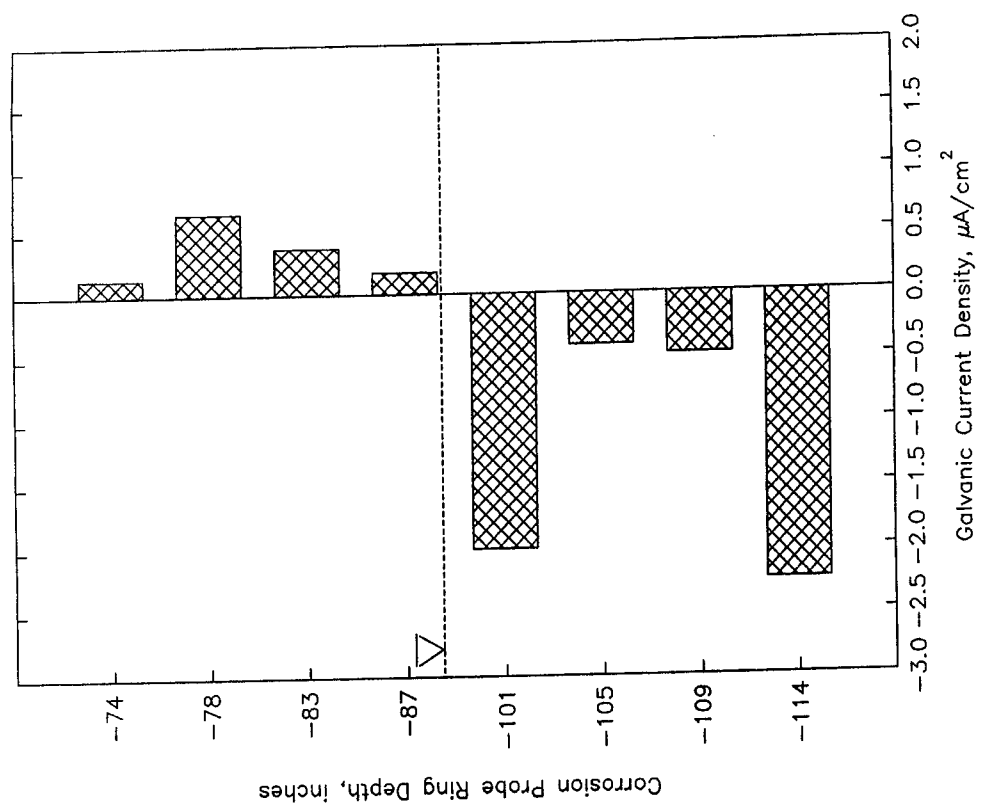
Figure M-2. Example of Galvanic Current Distribution Along a Field Corrosion Probe in Soil.

APPENDIX N

Procedure for Making Polarization Resistance Measurements With a Corrosion Probe in a Soil Environment

PROCEDURE FOR MAKING POLARIZATION RESISTANCE MEASUREMENTS WITH A CORROSION PROBE IN A SOIL ENVIRONMENT

1.0 SCOPE

This document describes the procedure for making polarization resistance measurements with a corrosion probe in a soil environment.

2.0 PURPOSE

The purpose of this document is to establish a field procedure for making polarization resistance measurements in corrosive soil layers, as defined from laboratory test results. Electrochemical reactions can occur uniformly on a metal surface leading to uniform corrosion of the metal. For most underground steel structures, rates of uniform corrosion are usually low and rarely cause service failures. However, long-term measurements of uniform corrosion can be used to help assess the service life of steel piling and as an indicator as to when corrosion mitigation procedures should be considered.

3.0 APPLICABLE DOCUMENTS

3.1 Appendix M, NCHRP 10-46 Final Report.

3.2 Appendix P, NCHRP 10-46 Final Report.

3.3 Appendix Q, NCHRP 10-96 Final Report.

3.4 ASTM Method G 59, *Standard Practice for Conducting Potentiodynamic Polarization Resistance Measurements*.

4.0 EQUIPMENT

4.1 Corrosion probe.

4.2 High impedance potentiostat or commercial PR monitor.

4.3 High impedance voltmeter.

4.4 Assorted resistors.

4.5 Electrical leads.

4.6 Boring tool.

5.0 USE

5.1 An example of a corrosion probe is shown in **Figure N-1**.

5.1.1 The corrosion probe should be used where piling is designed to be at or extend both above and below the water table, and in soils having moderate to high possibility of uniform corrosion.

5.2 A qualified corrosion specialist should be consulted to assist in probe selection and field measurements.

5.3 PR measurements should be made periodically to ascertain the rate of uniform corrosion.

5.3.1 The frequency of measurements and test duration should be established by the person(s) conducting the test on a site-specific basis.
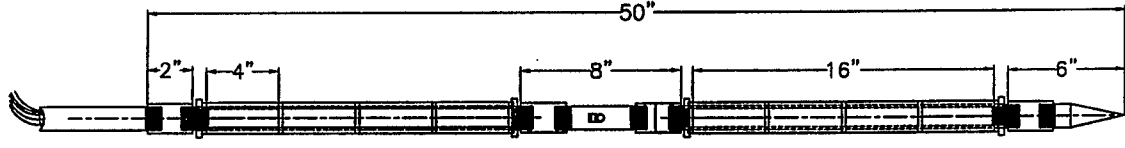

Figure N-1   Example of a Field Corrosion Probe for Soil.

5.3.2 For long-term corrosion monitoring, repeat measurements periodically at intervals to be determined based on the initial test results.

6.0 PROCEDURE FOR PROBE PLACEMENT

6.1 Measure the distance to the top of each probe ring from the probe tip, so that when the probe is placed in the soil to the desired depth, the depth of each ring is known.

6.1.1 The surface area of each probe ring should be measured and the values expressed in square centimeters.

6.2 Bore a small diameter hole (less than the diameter of the probe) in the soil to within 30 cm of the desired depth to aid in probe placement.

6.2.1 If steel piling is present, borings should be made as close to the pile as practicable using methodology appropriate for the type and depth of strata to be penetrated.

6.2.2 The hole should be drilled such that it extends through the most corrosive soil layers, based on the results of the soil analyses.

6.3 Install the probe in the small diameter hole.

6.3.1 A rotary hammer drill has been used successfully to place the probe shown in **Figure N-1**. The chosen placement technique should not damage the threaded ends of the probe or extensions.

6.3.2 Attach extension joints and bring electrical leads up through extension joints, as required.

6.3.3 Install a non-metallic test box on top of the last extension joint (if used) to house the electrical wires from each of the probe rings.

7.0 PR MEASUREMENTS - TWO ELECTRODE TECHNIQUE

7.1 Measurements of polarization resistance (PR) on each successive pair of steel rings on the probe.

7.1.1 PR measurements should be performed using a high impedance ($\geq 10^{12}$ ohms) potentiostat or commercial PR monitor/instrumentation.

7.1.2 Attach the counter and reference leads to the first ring and the working lead to the second ring. Measure the voltage (potential) between the rings using a high impedance voltmeter. (See Appendix P)

7.1.3 Scan ± 15 mV from the potential measured above. The scan should be conducted at a rate of 0.6 V/hr if automated, or in 5 mV steps every 30 seconds if performed manually. Follow this procedure to measure PR on remaining pairs of rings.

8.0 PR MEASUREMENTS - THREE ELECTRODE TECHNIQUE

8.1 PR measurements of two sets of steel rings on the probe.

8.1.1 One ring is to serve as the working electrode, an adjacent ring will serve as the reference electrode, and the two rings on either side of these will serve as the counter electrode.

8.1.2 PR measurements should be performed using a high impedance ($\geq 10^{12}$ ohms) potentiostat or commercial PR monitor/instrumentation.

8.1.3 Measure the voltage (potential) between the reference and working electrode rings.

8.1.4 Scan ± 15 mV from the potential measured above. The scan should be conducted at a rate of 0.6 V/hr if automated, or in 5 mV steps every 30 seconds if performed manually. Continue to measure PR on remaining pairs of rings.

9.0 REPORTING

9.1 Calculate the surface area of the working electrode. Convert current measurements to current density by dividing the current by the surface area. Plot potential (volts) as a function of current (amps). Determine the PR as the slope of the tangent of the curve where the current is zero. The PR should be reported as ohm-cm.

9.2 Convert PR to corrosion rate using the Stern-Geary equation and Faraday's Law:

$$Rate = \left(\frac{1}{PR}\right) * 20\ 802$$

where: Rate = Corrosion rate, mils per year
PR = Polarization resistance, ohm-cm^2
20 802 = Conversion factor (assumes an environmental factor of 0.044)

9.3 Corrosion rate is converted to rate of area loss using the following equation.

$$R = (CR)\ (L)\ (2.54\ E\text{-}3)$$

where: R = Rate of area loss, cm^2/year
CR = Electrochemical corrosion rate, mpy
L = Perimeter length, cm
2.54E-3 = Conversion factor for mils/year to cm/year

9.4 Corrosion rate measurements as a function of time can be used to help assess service life of the piling. (See Appendix Q)

APPENDIX O

Procedure for Making Potential Measurements with a Corrosion Probe and Potential Measurements of Existing Steel Piling in a Soil Environment

Figure O-1.   Example of a Field Corrosion Probe for Soil.

PROCEDURE FOR MAKING POTENTIAL MEASUREMENTS
WITH A CORROSION PROBE AND POTENTIAL MEASUREMENTS OF
EXISTING STEEL PILING IN A SOIL ENVIRONMENT

1.0 SCOPE

This document describes the procedure for measuring free-corrosion potentials of a corrosion probe and of existing steel piling in a soil environment.

2.0 SIGNIFICANCE

The free-corrosion potential is the potential of an electrode (steel probe ring or piling) measured with respect to a reference electrode or another electrode when no current flows from or to it. Correlations have been established between soil corrosivity and corrosion potentials of steel at or near the water table in that more corrosive soils generally have more negative potentials. Potential differences greater than 50 mV within stratified, unsaturated soil may indicate areas where galvanic corrosion could occur.

3.0 PURPOSE

The purpose of this document is to establish a field procedure for measuring free-corrosion potentials with a corrosion probe and of steel piling with respect to a reference electrode placed in corrosive strata, as identified through prior laboratory test results. Potential measurements used in conjunction with polarization resistance (PR) measurements can be used to identify potentially corrosive sites where steel piling may need to be visually examined periodically for life assessment estimates.

4.0 APPLICABLE DOCUMENTS

4.1 Appendix M, NCHRP 10-46 Final Report.

4.2 Appendix N, NCHRP 10-46 Final Report.

4.3 Lee, R. U. and A. H. Clark, "Corrosion of Steel Pilings in Soil," Corrosion '93, Paper No. 6., National Association of Corrosion Engineers, 1993.

5.0 EQUIPMENT

5.1 Corrosion probe containing a reference electrode.

5.2 High impedance voltmeter.

5.3 Electric leads.

5.4 Boring tool.

6.0 USE

6.1 A corrosion probe should be used for potential measurements at sites where steel piling is not present or where potential measurements are made at depth when piling is present. An example of a corrosion probe is shown in Figure O-1.

6.1.1   The corrosion probe should be used where steel is designed to be at, or extend both above and below the water table, through soils having test results indicating moderate to high possibility of uniform corrosion.

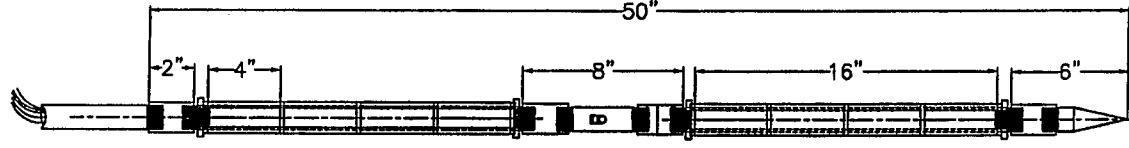6.2 A qualified corrosion specialist should be consulted to assist in probe selection and field measurements.

6.3 Potential measurements should be made in conjunction with galvanic current and polarization resistance measurements (Appendix M and N, respectively).

6.3.1 The frequency of measurements and test duration should be established by the person(s) conducting the test on a site-specific basis.

6.3.2 For long-term corrosion monitoring, repeat measurements periodically at intervals to be determined based on the test results.

7.0 PROCEDURE FOR PROBE PLACEMENT

7.1 Measure the distance to the top of each probe ring from the probe tip, so that when the probe is placed in the soil to the desired depth, the depth of each ring is known.

7.1.1 The surface area of each probe ring should be measured and the values expressed in square centimeters.

7.2 Bore a small diameter hole (less than the diameter of the probe) in the soil to within 30 cm of the desired depth to aid in probe placement.

7.2.1 If steel piling is present, borings should be made as close to the pile as practicable using methodology appropriate for the type and depth of strata to be penetrated.

7.2.2 The hole should be drilled such that it extends through the most corrosive soil layers, based on the results of the soil analyses.

7.3 Install the probe in the small diameter hole.

7.3.1 A rotary hammer drill has been used successfully to place the probe shown in Figure O-1. The chosen placement technique should not damage the threaded ends of the probe or extensions.

7.3.2 Attach extension joints and bring electrical leads up through extension joints, as required.

7.3.3 Install a non-metallic test box on top of the last extension joint (if used) to house the electrical wires from each of the probe rings.

8.0 POTENTIAL MEASUREMENTS

8.1 Measurement of the potential of steel probe rings or steel piling with respect to a reference electrode or another electrode.

8.1.1 For potential measurement of steel piling, abrade a small area of the steel pile to reveal a fresh metallic surface. If the surface cannot be abraded, a screw may be inserted into a drilled and tapped hole in the piling for a suitable electrical connection.

8.1.1.1 Using a high impedance voltmeter (multimeter) or equivalent device, connect an electrical lead from the fresh steel surface to the ground on the voltmeter. Connect the reference electrode on the probe to the positive terminal on the voltmeter. Be sure all connections are secure, clean, and not touching any other metallic surfaces. Turn on the voltmeter and read the value. Reverse the sign and record the potential value, sign, type of reference electrode used, and the location and depth of the corrosion probe reference electrode.

8.1.1.2 The minimum input impedance of the voltmeter should be 10^7 ohms. For high impedance soils, the voltmeter may "load down" and show significantly lower potential values. In these applications, a higher input impedance ($\geq 10^{12}$ ohms) buffer or electrometer should be used. Ideally, the buffer or electrometer should always be used to ensure a correct potential reading.

8.1.2 For potential measurements of probe rings, connect the electrical lead from the probe ring to be measured to the ground on a high impedance voltmeter. Connect the reference electrode lead to the positive terminal on the voltmeter. Reverse the sign and record the potential value, sign, type of reference electrode used, and the depth of the probe ring.

8.1.2.1 The minimum input impedance of the voltmeter should be 10^7 ohms. For high impedance soils, the voltmeter may "load down" and show significantly lower potential values. In these applications, a higher input impedance ($\geq 10^{12}$ ohms) buffer or electrometer should be used. Ideally, the buffer or electrometer should always be used to ensure a correct potential reading.

9.0 REPORTING

9.1 The potential values should be used for data analysis after reversing the sign of the measured values.

9.2 Evaluated data for changes in potential greater than 50 mV within the soil and follow guidelines set forth in **Figure K-4** of the NCHRP Recommended Practice in Appendix K.

APPENDIX P

Procedure for Estimating Service Life
of Existing Steel Piling

Figure P-1   Schematic of Calipers Used to Measure Pile Thickness.[Long, 1990]

PROCEDURE FOR ESTIMATING SERVICE LIFE OF EXISTING STEEL PILING

1.0 SCOPE

This document describes the procedure for estimating the rate of degradation and the remaining service life of existing bare steel piling.

2.0 PURPOSE

Results of dimensional loss and/or polarization resistance (PR) measurements are used to establish the degradation rate of existing bare steel piling. These data are then used to assess remaining service life of the piling to help in the decision-making process as to continued use in rehabilitated structures, possible cathodic protection installation, or repair/replacement of the piling.

3.0 APPLICABLE DOCUMENTS

3.1 Appendix M, NCHRP 10-46 Final Report (published herein).

3.2 Appendix N, NCHRP 10-46 Final Report (published herein).

3.3 Federal, state and local criteria for pile failure.

3.4 Long, R. P. and F. C. Huang, "Corrosion of Driven Steel Piles," Connecticut Department of Transportation, May 1990.

4.0 EQUIPMENT

4.1 Calipers (in absence of PR data).

4.2 Calculator.

5.0 ESTIMATING THE RATE OF PILE DEGRADATION

5.1 The rate of pile degradation is measured from (1) dimensional loss since pile installation, and/or (2) Electrochemical measurements converted to corrosion rates.

5.1.1 Dimension loss.

5.1.1.1 Dimension loss shall be determined by direct measurement with calipers or other applicable device. Figure P-1 is an example of calipers used to measure the thickness of piles.

5.1.1.2 The region to be measured shall first be blasted with walnut hulls or other abrasive. Clean, graded, walnut hulls are preferred for blasting corroded areas. If sand or other hard abrasive is used, care should be exercised to avoid removal of metal.

5.1.1.3 The cleaned steel shall be inspected and evaluated. The surface shall be examined for evidence of general and localized attack. If pitting is observed, the pit depths of several
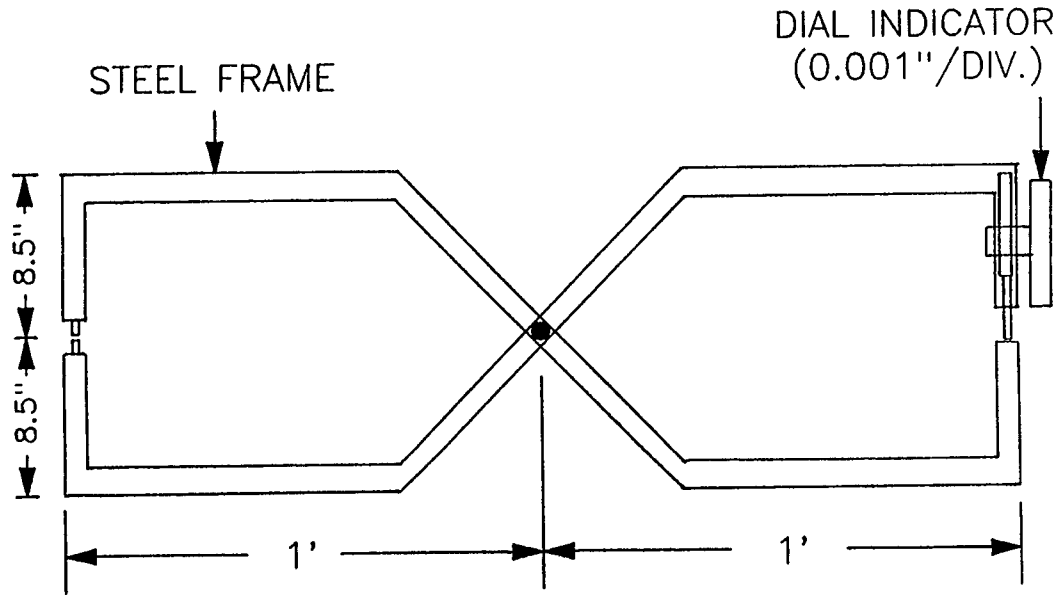
5.1.1.4 Calipers, or equivalent, shall be used to measure thickness of the steel pile. Loss in cross-sectional area shall be calculated from original specifications or measurements and the results converted to corrosion rates.

5.1.1.5 At minimum cross-section, determine remaining cross-sectional area from caliper readings. Convert to average rate of area loss using the following equation:

$$Rate\ of\ Area\ Loss = \frac{A_{initial} - A_{final}}{Years\ of\ Exposure}$$

5.1.2 Electrochemical Measurements.

Two types of electrochemical corrosion rate measurements may be performed, polarization resistance (PR) and/or galvanic current (GC). The time average value of the electrochemical parameter test period should be used for the calculation where both measurements are performed. The two should be summed:

Corrosion Rate (Total) = Corrosion Rate $_{(PR)}$ + Corrosion Rate $_{(GC)}$

5.1.2.1 PR values are converted to corrosion rate using the following equation:

$$Rate = \left(\frac{1}{PR}\right) * 20\ 802$$

where: Rate = Corrosion rate, mils per year
PR = Polarization resistance, ohm-cm^2
20 802 = Conversion factor (assumes an environmental factor of 0.044)

5.1.2.2 Galvanic current measurements are converted to a corrosion rate using the following equation:

$$CR_{(galvanic)} = \frac{i\ x\ 0.47278}{A}$$

where: $CR_{galvanic}$ = Galvanic corrosion rate, mpy
I = Galvanic current, μA
A = Surface area of corrosion probe ring, cm^2
0.47278 = Conversion factor specific to carbon steel

5.1.2.3 Corrosion rate is converted to rate of area loss using the following equation:

R = (CR) (L) (2.54 E-3)

where: R = Rate of area loss, cm^2/year
CR = Electrochemical corrosion rate, mpy
L = Perimeter length, cm
2.54E-3 = Conversion factor for mils/year to cm/year

6.0 DETERMINATION OF SERVICE LIFE

6.1 Criteria for pile failure.

6.1.1 Failure of steel piling, from a corrosion standpoint, is an average loss equal to 50% of the original cross-sectional area.

6.1.1.1 The section-loss criteria is to be used in addition to existing federal, state, and local criteria to determine pile failure.

6.2 Service life calculation.

6.2.1 The determination of service life is calculated from the rate of degradation determined in Section 5.0 and the criteria for pile failure given in Section 6.1.

6.2.2 The value for 50% of the cross-sectional area (Section 6.1), divided by the rate of area loss in Section 5.0, will give an estimate of the service life in years.

7.0 EVALUATION OF RESULTS

7.1 Compare estimate of service to design life of the structure.

7.1.1 Repair or replace pile if there is no remaining service life.

7.1.2 Install cathodic protection if remaining service life is less than design life.

7.1.3 Install corrosion probe (Figure M-1, Appendix M, NCHRP 10-46 Final Report, published herein) and monitor galvanic current if remaining service life is about equal to design life.

7.1.4 No action is necessary if remaining service life is greater than design life.

APPENDIX Q

Glossary of Terms

GLOSSARY OF TERMS

anode: The electrode of an electrolytic cell at which oxidation is the principal reaction. (Electrons flow away from the anode in the external circuit. It is usually the electrode where corrosion occurs and metal ions enter solution.)[1]

boulders: Particles of rock that will not pass a 300 mm square opening.[2]

cathode: The electrode of an electrolytic cell at which reduction is the principal reaction. (Electrons flow toward the cathode in the external circuit.)[1]

cation-exchange capacity (CEC): The sum total of exchangeable cations that a soil can absorb. Expressed in milliequivalents per 100 grams or per gram of soil.[3]

clay: (a) A natural substance of soft rock, which when mixed with water, forms a pasty, moldable mass that preserves its shape when air dried; (b) soil consisting of inorganic material the grains of which have diameters smaller than 0.005 mm; (c) fine-grained soil that has a high plasticity index in relation to the liquid limit and consists mainly of particles less than 0.074 mm (passing No. 200 sieve) in diameter.[4]

clay mineral: Finely crystalline; hydrous silicates with a crystal structure of the two-layer type (e.g., kaolinite) or three-layer type (e.g., montmorillonite) in which silicon and aluminum ions have tetrahedral coordination with respect to oxygen.[4]

coarse gravel: see gravel, coarse.

coarse sand: see sand, coarse.

cobble: Particles of rock that will pass a 300 mm square opening and be retained on a 76.2 mm sieve.[2]

conductivity: The reciprocal of the resistance in ohms measured between opposite faces of a centimeter cube of an aqueous solution at a specified temperature.[5]

corrosion: The chemical or electrochemical reaction between a material, usually a metal, and its environment that produces a deterioration of the material and its properties.[1]

corrosion potential: The potential of a corroding surface in an electrolyte relative to a reference electrode measured under open-circuit conditions.[1]

disturbed samples: Soil samples obtained in a manner which destroys the original orientation and some of the physical properties of the naturally deposited material.[3]

disturbed soil: Soil in which the original orientation and physical properties have been altered.

Eh: see redox potential.

extractable acidity: syn: exchangeable acidity, extractable hydrogen. The measurement of exchangeable ions that contribute to soil acidity.

fill: Man-made deposits of natural soils, rock products, or waste materials.[3]

fine gravel: see gravel, fine.

fine sand: see sand, fine.

gravel: Particles of rock that will pass a 76.2 mm sieve and be retained on a 4.75 mm (No. 4) sieve.[2]

gravel, coarse: Particles of rock that will pass a 76.2 mm sieve and be retained on a 19 mm sieve.[2]

gravel, fine: Particles of rock that will pass a 19 mm sieve and be retained on a 4.75 mm (No. 4) sieve.[6]

hydrolysis: (a) The reaction of a compound with water creating new chemicals. (b) The addition of water to a substance to alter its nature or create new substances.[7]

macrocell corrosion: Corrosion from galvanic current flow on metallic surface exposed to soil layers having differential oxygen concentrations or ionic strengths.

medium sand: see sand, medium.

natural soil: see soil.

nonmarine: Not relating to a body of brackish or saltwater (sea).

open-circuit potential: The potential of an electrode measured with respect to a reference electrode or another electrode when no current flows to or from it.[1]

oxidation: The loss of electrons by a constituent of a chemical reaction.

permeability: The capacity of a rock to conduct liquid or gas.

pH, soil: The negative logarithm of the hydrogen-ion activity of a soil. The degree of acidity (or alkalinity) of a soil as determined by means of a glass or other suitable electrode or indicator at a specified moisture content or soil-water ratio, and expressed in terms of the pH scale.[3]

polarization: The change from the open-circuit electrode potential as a result of the passage of current.[1]

polarization resistance: The slope $\Delta E/\Delta i$ at the corrosion potential of a potential (E) - current density (I) curve. (It is inversely proportional to the corrosion current density when the polarization resistance technique is applicable.)[1]

porosity: The ratio, usually expressed as a percentage of (a) the volume of voids of a given soil or rock mass, to (b) the total volume of the soil or rock mass.[2]

potentiostat: An instrument for automatically maintaining an electrode in an electrolyte at a constant or controlled potential with respect to a suitable reference electrode.[1]

redox potential: (Eh, oxidation-reduction potential) The potential of a reversible oxidation-reduction electrode measured with respect to a reference electrode, corrected to the hydrogen electrode, in a given electrolyte.[1]

reduction: The gain of electrons by a constituent of a chemical reaction.

resistance: The opposition that a substance offers to the flow of electric current, measured in ohms.[7]

resistivity: Electrical resistance per unit length, area, or volume. Given in ohms per meter, ohms per square meter, or ohms per cubic meter. See resistance.[7]

rust: A corrosion product consisting primarily of hydrated iron oxide. (A term properly applied only to ferrous alloys.)[1]

sand, coarse: Particles of rock that will pass a 4.75 mm (No. 4) sieve and be retained on a 2.00 mm (No. 10) sieve. [2]

sand, fine: Particles of rock that will pass a 425 μm (No. 40) sieve and be retained on a 75 μm (No. 200) sieve. [2]

sand medium: Particles of rock that will pass a 2.00 mm (No. 10) sieve and be retained on a 425 μm (No. 40) sieve. [2]

silt: (a) Soil passing a 75 μm (No. 200) sieve that is non-plastic or very slightly plastic and that exhibits little or no strength when dry; (b) a fine-grained soil, or the fine-grained portion of a soil, with a plasticity index less than 4. [2]

soil: (a) The unconsolidated mineral material on the immediate surface of the Earth that serves as a natural medium for the growth of land plants; (b) the unconsolidated mineral matter on the surface of the Earth that has been subjected to and influenced by genetic and environmental factors of: parent material, climate (including moisture and temperature effects), macro- and microorganisms, and topography, all acting over a period of time and producing a product, soil, that differs from the material from which it is derived in many physical, chemical, biological, and morphological properties and characteristics. [3]

soil moisture: Water contained in the soil. [3]

undisturbed samples: A soil sample that has been obtained by methods in which every precaution has been taken to minimize disturbance to the sample. [3]

undisturbed soil: In situ soil; not disturbed.

uniform corrosion: Corrosion distributed uniformly over the surface of a metal.

water table: The upper surface of groundwater or that level below which the soil is saturated with water; locus of points in soil water at which the hydraulic pressure is equal to atmospheric pressure. [3]

REFERENCES

1. _____, Annual Book of ASTM Standards, American Society for Testing and Materials, Philadelphia, Pennsylvania, Vol. 03.02, 1992.

2. _____, Annual Book of ASTM Standards, American Society for Testing and Materials, Philadelphia, Pennsylvania, Vol. 04.08, 1992.

3. Roberts, D. W., "Soil Properties Classification and Hydraulic Conductivity Testing," EPA Report No. EPA/530-SW-84-925, United States Environmental Protection Agency, Office of Research and Development, (NTIS PB87-155784), March 1984.

4. _____, Dictionary of Geological Terms, American Geological Institute, 1962.

5. _____, Annual Book of ASTM Standards, American Society for Testing and Materials, Philadelphia, Pennsylvania, Vol. 11.01, 1995.

6. Hendershot, W. H. and H. Lalande, "Soil Reaction and Exchangeable Acidity," Soil Sampling and Methods of Analysis. Ed: M. R. Carter, Lewis Publishers, 1993, pp. 141-144.

7. Gibilisco, Stan, The Concise Illustrated Dictionary of Science and Technology, Tab Books, Blue Ridge Summit, Pennsylvania, 1993.